DEVELOPMENT OF A GUARDED HOT PLATE THERMAL CONDUCTIVITY MEASURING APPARATUS FOR THERMOPLASTIC MATERIALS

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DEVELOPMENT OF A GUARDED HOT PLATE THERMAL CONDUCTIVITY MEASURING APPARATUS FOR THERMOPLASTIC MATERIALS

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NOMENCLATURE

Latin Letters

Symbol	Definition	Units
A	area, metering area	m^2
A_1	area of cylindrical side of central heater section	m^2
ΔA	uncertainty in measurement of metering area	m^2
a_0	numerical constant	W/m-°C
b_0	numerical constant	W/m-°C^2
c	numerical constant	--
C_p	specific heat	J/gm-°C
d	guard ring width	m
E_{max}	maximum voltage	V
e	base of natural logarithm	--
F	shape factor	--
g	acceleration of gravity	m/s^2
I_{max}	maximum current	A
k	thermal conductivity	W/m-°C
k_{exp}	experimentally measured thermal conductivity	W/m-°C
k_f	fluid thermal conductivity	W/m-°C
k_e	equivalent thermal conductivity	W/m-°C
k_{max}	maximum specimen thermal conductivity	W/m-°C
L	specimen thickness	m

Symbol	Definition	Units
L_{min}	minimum specimen thickness	m
ΔL	uncertainty in measurement of specimen thickness	m
ℓ	radius of the metering section	m
N_{Ra}	Rayleigh number	--
p	compressive force on pressure pad	N
q	rate of heat flow	W
q_{max}	maximum heat flow	W
Δq	uncertainty in measurement of heat flow	W
q_o	heat flow across guard gap	W
$q_{convection}$	convective heat transport	W
$q_{conduction}$	conductive heat transport	W
$q_{radiation}$	radiative heat transport	W
$\vec{q}''$	heat flux vector	W/m^2
q''	heat flux	W/m^2
q'''	heat generation per unit volume	W/m^3
R	electrical resistance	Ω
r	radius of pressure pad	m
T	temperature	°C
$\bar{T}$	mean specimen temperature	°C
T_c	temperature of cold surface of specimen	°C,°K
T_e	temperature of edge of specimen	°C
T_g	temperature of guard surface plate	°C
T_h	temperature of hot surface of specimen	°C,°K

Symbol	Definition	Units
$\Delta(T_h - T_c)$	uncertainty in temperature drop across specimen	°C
$(T_h - T_c)_{max}$	maximum temperature drop across specimen	°C
$T_h - T_g$	temperature difference between central heater and guard ring	°C
t	time	s
x	variable distance	m

Greek Letters

Symbol	Definition	Units
α	thermal diffusivity	m^2/s
β	coefficient of thermal expansion	$°K^{-1}$
ε_e	edge loss error	--
ε_g	thermal imbalance error	--
ε_t	sum of edge loss and thermal imbalance error	--
ρ	density	kg/m^3
σ	Stefan Boltzman Constant	$W/m^2\text{-}°K^4$
τ	torque	N-m

SUMMARY

This thesis describes the analysis, design, and testing of a thermal conductivity measuring apparatus for thermoplastic materials in conformance to the ASTM C-177-71 Standard.

Theoretical error analyses of the edge heat loss and the thermal imbalance across the guard gap were performed in order to determine the physical dimensions of the apparatus and the required accuracy of the measurement and control systems. In order to determine the accuracy of the apparatus, a control material was obtained and measurements were made with three different methods by three independent sources. These methods consisted of the ASTM guarded hot plate, the thermal comparator, and a device that utilized a "boiling/condensing liquid" for the heat source/sink. Two sets of measurements at a one month interval were then made at four different temperatures to verify the repeatability of the apparatus.

These tests along with the error analysis indicated that the device was accurate to within ±5.4 percent; and, that the measurements were repeatable to within ±0.5 percent of the mean of the data obtained.

The apparatus was used to measure the thermal conductivity of three thermoplastic materials whose thermal conductivities were unavailable in the literature.

CHAPTER I

THEORY OF THERMAL CONDUCTIVITY MEASUREMENT AND BACKGROUND

I.1. Theory of Thermal Conductivity Measurement

Historically, the fundamental law which quantitatively defines the thermal conductivity of a substance is attributed to Jean Fourier. The vectorial form of the Fourier Law for a heterogeneous, isotropic, substance is given by:

$$\vec{q} = -k\vec{\nabla}T. \tag{1}$$

In Equation (1), $\vec{q}$ is the heat flux at a point, $\vec{\nabla}T$ is the temperature gradient at the point, and k is the thermal conductivity of the substance at the point. Equation (1) along with the general heat conduction equation forms the basis for all methods of measuring the thermal conductivity of a substance. The general heat conduction equation for a heterogeneous, isotropic substance is given by:[1]

$$\rho c_p \frac{\partial T}{\partial t} = \vec{\nabla}\cdot(k\vec{\nabla}T) + q'''. \tag{2}$$

In Equation (2), the density, ρ, the specific heat, c_p, the internal heat generation q''', and k are scalar quantities which in general are functions of the temperature. More generally, for a non-isotropic substance, k is a tensor. However, by an appropriate change of variables the same form of Equation (2) also applies to non-isotropic substances.[1] As its differential form implies, the equation is strictly valid only for a continuum. In principle, the thermal conductivity may be experimentally evaluated once an exact solution of Equation (2) is obtained in terms of position, time, and the material properties. From a practical point of view, the thermal conductivity is most easily experimentally measured by utilizing Equation (2) in a greatly simplified form. One such form in Cartesian coordinates is:

$$\frac{d^2T}{dx^2} = 0. \tag{3a}$$

The simplifying assumptions which give rise to Equation (3a) are:

(1) One-dimensional heat flow in the "x" direction

(2) Steady state

(3) No internal heat generation;

(4) The thermal conductivity is independent of temperature

When these assumptions are physically realized, Equation (3a) may be integrated to give:

$$T(x) = C_1x + C_2 \tag{3b}$$

Assuming the boundary conditions are:

$$@\ x = 0; \qquad T = T_h$$
$$@\ x = L, \qquad T = T_c$$

the constants of integration may be evaluated to yield:

$$T(x) = \{\frac{T_c - T_h}{L}\}x + T_h \tag{4}$$

Substitution into Equation (1) gives:

$$q'' = -k\frac{dT}{dx} = -\frac{k(T_c - T_h)}{L} = \frac{q}{A} \tag{5}$$

Hence:

$$k = \frac{Lq}{(T_h - T_c)A} \tag{6}$$

In Equation (6), q is the total heat flow and A is the area of flow. In reality, the thermal conductivity of all substances is a function of temperature and hence position. For a small temperature difference, the thermal conductivity may be assumed to vary linearly with temperature or; $k(T) \approx a_0 + b_0T$. It may be shown for this case that Equation

(6) becomes:[2]

$$k\left(\frac{T_h+T_c}{2}\right) = \frac{Lq}{(T_h-T_c)A} \tag{7}$$

All quantities on the right hand side of Equation (7) can be experimentally measured and hence a value for k may be calculated at the mean temperature, $\bar{T} = \frac{T_h+T_c}{2}$.

I.2. Physical Interpretation of Thermal Conductivity

Although the Fourier Law defines the thermal conductivity mathematically, it does not give any physical interpretation of the quantity. In fact, only in recent years has any insight been gained in understanding the property in terms of kinetic theory. Since heat is thermal energy in transition, and thermal energy is disordered mechanical energy, the basic mechanism of heat transfer is the transport of kinetic energy. Also, since it is generally observed that the more condensed phases of matter have higher thermal conductivities, it is apparent that the mechanism of energy transport is highly dependent on the atomic and/or molecular structure of the material. Specifically, for substances such as polymeric solids, the mechanism depends upon whether the material is amorphous or crystalline, the molecular weight, and the chemical constituents of the chain backbone and side groups.[3] Generally, for crystalline polymers, there are theories of quantized lattice vibrations whereby the thermal energy transport is analyzed in terms of phonon scattering. For amorphous polymers, the energy transport is related to the segmental mobility of polymer subchains. The relation of the thermal transport phenomenon to molecular weight distribution and the chain constituents is much less clear. In fact, currently there is no general theory for the mechanism of thermal energy transport in polymeric solids. Hence, at the present time, the thermal conductivities of polymers are usually determined by experimental investigation.

I.3. Sources of Error in the Measurement of Thermal Conductivity

The errors encountered in the measurement of thermal conductivities are largely a function of how closely the experimental apparatus can simulate the conditions specified by the particular form of the heat conduction equation. These errors are conveniently classified as determinant and indeterminant errors.[4] The determinant errors are those which can be attributed to a specific system, and can only be compensated for by a band of errors applied to the observed results. Indeterminant errors are those for which a probability exists that a range of values will occur in a series of observations on a specific quantity. This type of error can only be assessed after numerous observations. The total error is the sum of the determinant and indeterminant errors.

Specifically the determinant errors are those due to inaccurate measurement of the physical quantities appearing in the heat conduction equation; namely, specific heat, density, temperature, heat flow area, time, length of heat flow path, and the quantity of heat flow. The indeterminant errors are primarily connected with the character of the heat flow and the boundary conditions. For Equation (3a) these are:

(1) The steady state assumption which cannot be absolutely attained during measurements

(2) Unidirectional heat flow which cannot be absolutely assured because of:

  (a) Heat loss or gain at the edges of the specimen through imperfect side insulation

  (b) The temperature differences that may exist between the heater test area and adjacent material

  (c) Contact resistance between the heater plate and the samples

Many analyses have been developed to assess the order of magnitude of the indeterminant errors associated with Equation (3a); specifically in regard to the twin guarded hot plate. A review of these analyses will be given in Section III of this thesis. Subsequently, two of the analyses will be applied in a design procedure to determine physical dimensions and operating parameters of a twin guarded hot plate device for measurement of the thermal conductivity of polymeric solids.

Ideally, the best way to assess the accuracy of any thermal conductivity measuring device is to compare the measured results with that of a material of known thermal conductivity. However, there is no agreement on a single standard thermal conductivity material for polymeric solids.

I.4. Methods of Measurement of Thermal Conductivity

The basic thermal conductivity measurement techniques can be classified as steady state or transient methods. Since those of a transient nature require simultaneous measurement of time, density, specific heat, area, length, and quantity of heat flow, it is expected that these methods will have more measurement errors associated with them when compared to the steady state techniques. On the other hand, the steady state method only requires measurement of heat flow, temperature, area, and length. Hence, it is the standard method specified by the ASTM. It was primarily for this reason that the steady state method was employed in the measurement of the thermal conductivity of polymeric solids in this thesis.

CHAPTER II

THE ASTM C177-71 STANDARD

II.1. Scope of the Standard

The standard specification for the design, construction, and operation of a guarded hot plate apparatus to measure the thermal conductivity of solid insulating materials is the ASTM C-177-71 Standard.[5] This standard applies only to measurements on material test specimens having thermal conductances not in excess of 60 W/m^2-°C and within certain limits of thickness for a given set of physical dimensions of the hot plate. The thermal conductance is defined as the ratio of thermal conductivity to the specimen thickness. The standard describes two different types of guarded hot plates; a low temperature guarded hot plate and a high temperature hot plate. The low temperature guarded hot plate may be used over a temperature range such that the cold plate temperature may be as low as 77°K and the hot plate temperature as high as 550°K. The high temperature guarded hot plate is used above 550°K. Since the upper temperature limit of 550°K is above the maximum use temperature of most polymeric solids, the low temperature guarded hot plate was selected to measure the thermal conductivity of polymers.

The essential components of the apparatus consist of two identical test specimens of known thickness and area, each of which is interposed between two isothermal metal plates. The assembly is clamped together to assure good thermal contact between adjacent surfaces. Heat is removed from the cold plates by a constant temperature liquid flowing through a heat exchanger. The cold plate temperature may be maintained constant either by the flowing liquid or by a separate heater plate that is automatically controlled. A regulated power supply provides energy to the heaters of the test area in order to establish the desired temperature gradient through the test specimens. A guard ring located around the central heater is used to help assure unidirectional heat flow. Once steady state is established, the thermal conductivity may be calculated by measurement of the quantities in Equation (7). It is well to note that the ASTM C-177-71 Standard does not establish sufficient design and construction details to cover the many contingencies that might arise for one not having experience in the theory of heat transfer, temperature measurement and control, instrumentation, and mechanical design. Neither does the ASTM Standard indicate where a source of this type of detailed information applicable to guarded hot plates may be obtained. The ASTM Standard only provides general criteria which experience has demonstrated to be essential for reliable and reproducible measurements. Even when the ASTM Standard is adhered to, the literature indicates that about 75 percent of the measured thermal conductivities on similar samples will be in agreement within ±3 percent of the mean. However, some individual results may vary by as much as +13 percent and -16 percent.[6]

II.2. The Low Temperature or "Metal-Surfaced Plate" Guarded Hot Plate

The general features of the low temperature guarded hot plate are essentially the same as for the high temperature guarded hot plate except for the following significant differences:

(a) The low temperature guarded hot plate must have metal surface plates, whereas the surface plates for high temperature guarded hot plates may be constructed from a refractory material.

(b) The low temperature guarded hot plate must have a definite guard gap, whereas the high temperature guarded hot plate may or may not have a definite guard gap.

II.2.1. Central Heater Section Design and Construction

The basic geometry of the hot plate apparatus may either be round or square. The literature seems to indicate that most plates are square. The reason for this choice is probably because of easier sample preparation for this geometry. However, it is believed that the round plate configuration is better from a temperature control aspect because of symmetry. The central heating unit consists of a metering section and a guard ring. The metering section consists of a central heater and surface plates. The heat flow through the central section is accurately controlled and measured. The heat generation in the central heater must be measured to an accuracy of 0.5 percent and controlled to the same accuracy. The guard ring consists of one or more guard heaters and guard surface plates. The use of metal surface plates on both the central and guard heaters is specified in order to assure that an isothermal heat source is in good thermal contact with the test specimens. All surface plates are usually constructed from a relatively non-corroding metal of high thermal conductivity; e.g., oxygen-free copper. The maximum departure from a flat surface is specified to be 0.25 mm/m. Departures from this requirement can result in measured values of the thermal conductivity that are too low because of the presence of air gaps between the heater plates and specimens.

The ASTM Standard requires that the maximum separation between the central surface plates and guard ring surface plates is 3 mm. This dimension is illustrated in Figure 1. For plates constructed from a material of high thermal conductivity such as copper, the separation between the heater winding of the central heater and contiguous guard must not exceed 20 mm. This dimension is also shown in Figure 1. The purpose of this requirement is to assure an isothermal condition on both the metering surface plate and

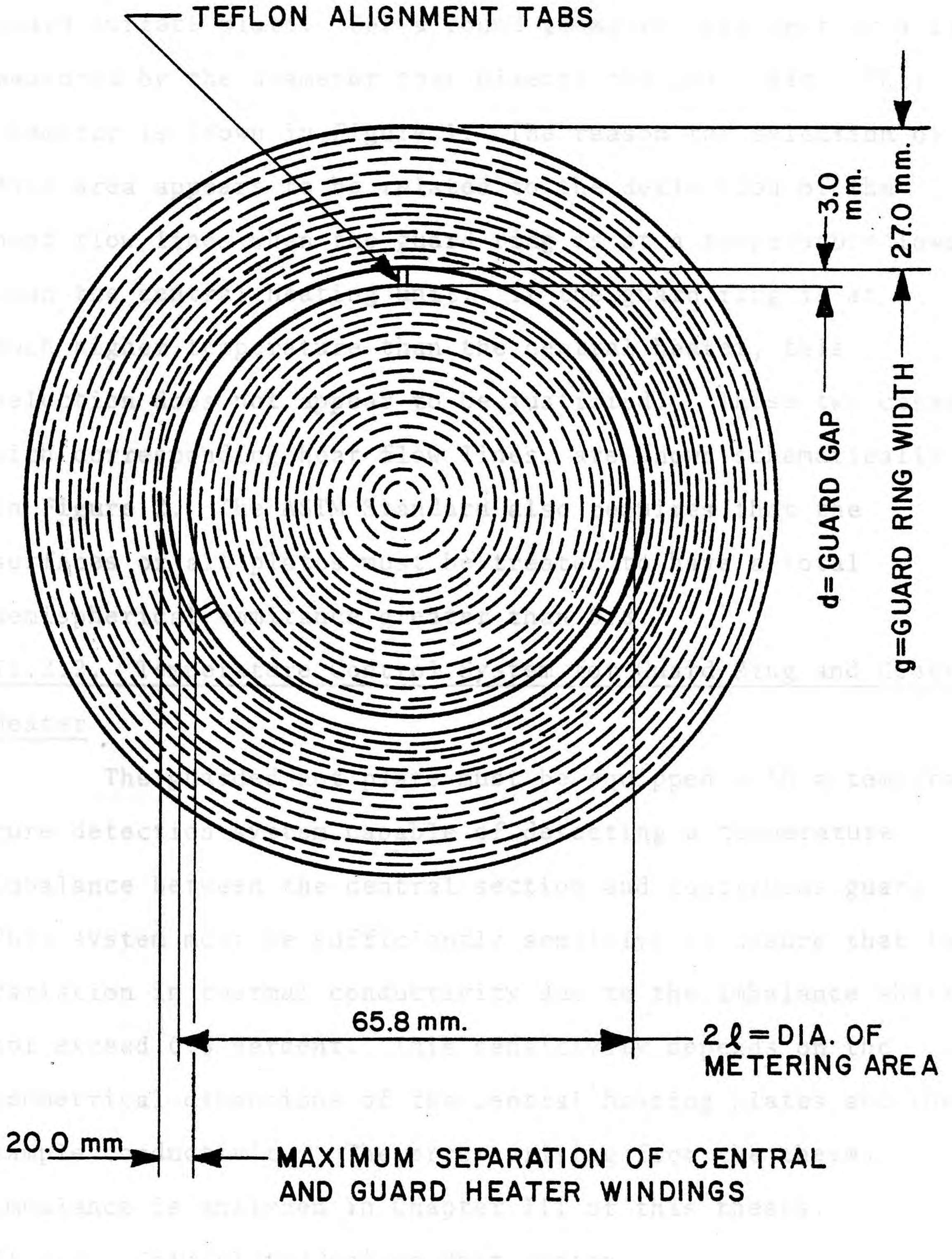

Figure 1. Central Heater Geometry

guard surface plate. For a round geometry, the test area is measured by the diameter that bisects the guard gap. This diameter is shown in Figure 1. The reason for selection of this area appears to be related to the deflection of the heat flow lines when the guard ring is at a temperature lower than the central heating unit. If the guard ring is at a much higher temperature than the central heater, this selection does not appear to be justified. These two cases, with corresponding heat flow lines, are shown schematically in Figure 2. The ASTM Standard also requires that the surfaces of all plates must be treated to have a total hemispherical emmitance greater than 0.8.

II.2.2. Temperature Control System for Guard Ring and Central Heater

The guarded hot plate must be equipped with a temperature detection system capable of detecting a temperature imbalance between the central section and contiguous guard. This system must be sufficiently sensitive to assure that the variation in thermal conductivity due to the imbalance shall not exceed 0.5 percent. This sensitivity depends on the geometrical dimensions of the central heating plates and the sample conductivity. The error arising from the thermal imbalance is analyzed in Chapter III of this thesis.

II.2.3. Cold Plate/Cooling Unit Design

The cold plates must have surface dimensions at least as large as those of the central unit (both central heater

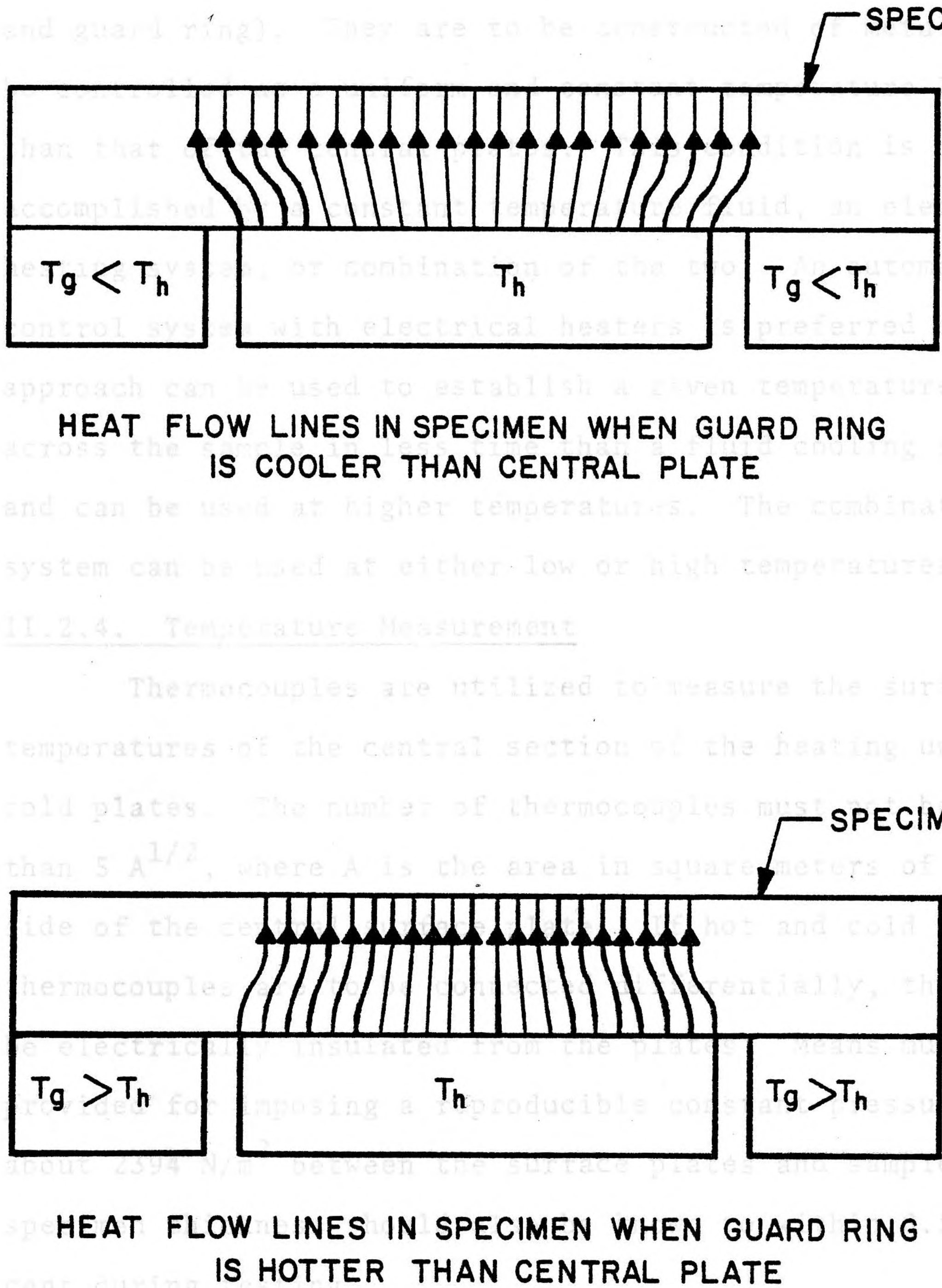

Figure 2. Deflection of Heat Flow Lines Due to Thermal Imbalance Between Central Heater and Guard Ring

and guard ring). They are to be constructed of metal and to be controlled at a uniform and constant temperature lower than that of the central plates. This condition is best accomplished by a constant temperature fluid, an electrical heating system, or combination of the two. An automatic control system with electrical heaters is preferred since this approach can be used to establish a given temperature drop across the sample in less time than a fluid cooling system and can be used at higher temperatures. The combination system can be used at either low or high temperatures.

II.2.4. Temperature Measurement

Thermocouples are utilized to measure the surface temperatures of the central section of the heating unit and cold plates. The number of thermocouples must not be less than 5 $A^{1/2}$, where A is the area in square meters of one side of the central surface plate. If hot and cold plate thermocouples are to be connected differentially, they must be electrically insulated from the plates. Means must be provided for imposing a reproducible constant pressure of about 2394 N/m^2 between the surface plates and sample. The specimen thickness should also be known to within 0.5 percent during testing.

The method for determining the temperature drop across the test specimens is left to the judgement of the experimenter. For non-rigid specimens with flat surfaces that conform well to the working surfaces of the plates; and with thermal conductances less than 10 W/m^2-°C, the temperature drop can be taken to be that indicated by thermocouples permanently mounted in the hot and cold surface plates. Thermoplastic materials are examples of such materials that generally satisfy the above conditions. For rigid materials, such as glass, the ASTM Standard states that it is imperative that the specimen surfaces be parallel and flat to within 0.25 mm/m. One method suggested for testing rigid materials is to interpose a thin sheet of material with known thermal conductivity between the surface plates and rigid specimen. The thermal conductivity of the sheet material should be high relative to that of the specimen. Also, this sheet should be non-rigid to achieve the desired purpose. The ASTM Standard does not define, however, what a definite criterion is for determining whether or not a given material is to be considered "rigid." Neither does it suggest typical "thin sheet materials" to be used in construction of the composite specimen. The thermocouples to be used in the surface plates must not be more than 0.57 mm in diameter (No. 23 B & S Gage). If thermocouples are to be attached to the specimen surface, the maximum wire diameter is 0.29 mm (No. 29 B & S Gage). The thermocouples must be fabricated either from calibrated thermocouple wire or from wire certified by the manufacturer to conform to ASTM Tables E-230. Temperature-EMF tables for thermocouples must be within the standard limits of error in Table 15 of these tables. The standard does not require thermocouples to be calibrated if the wire conforms to the above requirements. Thermocouple EMFS are to be measured on a voltage-measuring system having a sensitivity of ±1 μv and an accuracy of ±0.1 percent. This corresponds to an instrument resolution of about 0.1°C.

II.2.5. Heat Loss From Edge of Specimen

Heat loss from the edge of the specimen is to be restricted by edge insulation. This heat loss is a complicated function of specimen geometry and properties and is examined in Chapter III of this thesis. The criterion given in the ASTM Standard for determination whether or not sufficient edge insulation is present is given as follows:

$$\frac{T_e - \bar{T}}{T_h - T_c} < 0.10 \tag{8}$$

In Equation (8)

T_e is the edge temperature of the specimen

$\bar{T}$ is the mean temperature of the specimens

$(T_h - T_c)$ is temperature drop across the specimen

The ASTM Standard does not indicate the origin or the basis for the criterion in Equation (8).

II.2.6. Testing of Specimens

The method of specimen preparation, the testing procedure, the required calculations, and report format are given in Sections 6, 7, 8, and 9, respectively, of the ASTM

Standard. These requirements are discussed in Chapter V of this thesis.

CHAPTER III

ERROR ANALYSIS OF THE GUARDED HOT PLATE

III.1. Literature Review

A number of analyses have been performed on the guarded hot plate apparatus in order to access the magnitude of the indeterminant errors associated with the method. As stated in Section I.3., these errors are largely dependent upon the degree to which the assumptions in Equation (3a) can be reproduced on a test specimen of limited dimensions. In particular, once steady state is attained, a primary source of indeterminant error is associated with the non-unidirectional nature of the heat flow. Deviations from unidirectional heat flow can arise because of heat loss from the edge of the specimen and the thermal imbalance between the metering section and the guard ring. Analyses of the error arising from edge loss have been performed by Somers and Cyphers,[7] Woodside,[8] Donaldson,[6] and Pratt.[9] Their results are all in substantial agreement as has been confirmed by numerical investigations,[10,11] analog computation,[12] and somewhat by experiment.[13,14] In addition, theoretical analyses have also been performed by Woodside[15] and Donaldson[6] in order to determine the error associated with the thermal imbalance between the metering section and guard ring.

DePonte and DiFilippo[16] have attempted to consolidate these efforts into a design procedure to assist in the development of a guarded hot plate apparatus for a given performance. Their procedure is strictly applicable only to a square geometry; however, the results obtained by Somers and Cyphers[7] indicate that the predicted error due to edge loss for cylindrical geometries differs only negligibly from that for a square geometry if the ratio of sample thickness to its characteristic length is small (≈ 0.2). No analysis of the error arising from the thermal imbalance for cylindrical geometries was available; hence, prediction of these errors was obtained by defining appropriate characteristic dimensions of the apparatus and utilizing the analysis for square hot plates.

III.2. Edge Heat Loss Error

The analysis performed by Woodside[8] to predict the error due to edge heat loss was utilized in this thesis because of its simplicity. Woodside's derivation assumed that the two surfaces of the specimen are isothermal at temperatures $T_c = 0$ and T_h; and that the edge of the specimen is isothermal at a temperature $T^* = eT_h$, with $0 < e < 1$. The relationship between the "true" conductivity, k, and the experimentally measured conductivity, k_{exp}, as given by Woodside[8] is:

$$\left\{\frac{k}{k_{exp}}\right\}^{1/2} = \frac{\frac{\pi \ell}{L}}{e\,\ell n\left[\frac{\cosh\{\frac{\pi(g+\ell)}{L}\}+1}{\cosh\{\frac{\pi g}{L}\}+1}\right] + (1-e)\,\ell n\left[\frac{\cosh\{\frac{\pi(g+\ell)}{L}\}-1}{\cosh(\frac{\pi g}{L})-1}\right]} \tag{9}$$

where

- L is the specimen thickness
- g is the guard ring width from the gap centerline
- 2ℓ is the diameter of the metering section from gap center to gap center
- k is the actual specimen thermal conductivity
- k_{exp} is the experimentally measured value of the specimen conductivity.

The dimensions, g, and 2ℓ are shown in Figure 1.

For this thesis, a low value of $e = 0.25$ was assumed in order to obtain a conservative estimate of the edge loss error. This error, ε_e, is defined by

$$\varepsilon_e \equiv \frac{k_{exp}}{k} - 1 \tag{10}$$

A value of ε_e may be computed directly by substitution for $\frac{k}{k_{exp}}$ from Equation (9).

Qualitatively, the edge heat loss error increases when the specimen thickness increases, the guard ring width decreases, and/or the edge insulation is insufficient.

III.3. Thermal Imbalance Error

In the design of a guarded hot plate apparatus, it is imperative to evaluate the error due to thermal imbalance between the metering section and guard ring in order to select the proper temperature control system. The work of Woodside and Wilson[15] clearly demonstrates through accurate experimental data the magnitude of the error that results from thermal imbalance. Woodside and Wilson show that if the temperature imbalance is unity, then the net heat flow, q, from the metering section to the guard ring is given by:

$$q = q_o + ck \qquad (11)$$

In Equation (11):

q_o is the heat flow across the gap for a temperature imbalance of unity

ck is the heat flow from the metering section to the guard ring through the specimen having thermal conductivity k.

The symbol "c" represents a constant which depends upon the specimen thickness and gap geometry.

Woodside and Wilson[17] have demonstrated how the parameters in Equation (11) may be determined experimentally and also how they may be calculated. In particular, q_o, the total heat transport across the gap can be separated into the following components:

(a) Conduction and/or convection transfer across the air gap

(b) Radiative transfer across the gap

(c) Conduction through any mechanical supports which cross the gap

(d) Conduction through thermocouple wires that cross the gap

(e) Conduction through heater leads that cross the gap.

In calculating q_o, it is assumed that the above components are all non-interacting parallel mechanisms of heat transfer, and a one degree Celsius imbalance exists between the metering section and guard ring.

The parameter c was theoretically derived by Woodside[17] and has been simplified by DePonte and DiFilippo[16] to give

$$\frac{c}{\ell} = \frac{16}{\pi} \ln \{4 \div [1-\exp(\frac{-2\pi d}{L})]\} \tag{12}$$

In Equation (12), d is the gap width as shown in Figure 1.

Equation (12) was derived with the following assumptions:

1. The temperature distribution in the specimen is two dimensional.
2. The sample has been assumed to extend an infinite distance on either side of the gap as shown in Figure 3.

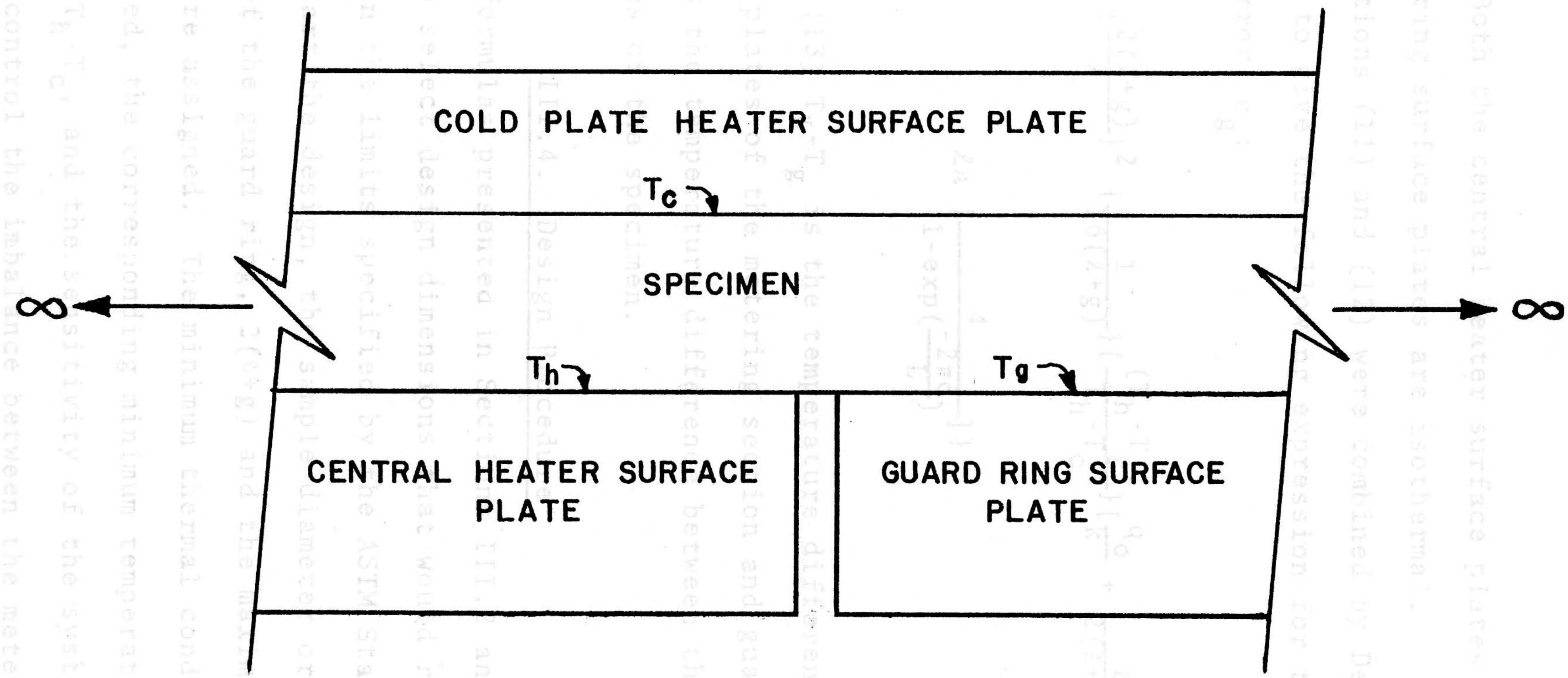

Figure 3. Assumed Geometry for Edge Heat Loss Error Analysis

3. Both the central heater surface plates and guard ring surface plates are isothermal.

Equations (11) and (12) were combined by DePonte and DiFilippo[16] to give the following expression for the thermal imbalance error, ε_g:

$$\varepsilon_g = \frac{L}{2(\ell+g)} \{\frac{2(\ell+g)}{\ell}\}^2 \{\frac{1}{16(\ell+g)}\}\{\frac{(T_h-T_g)}{T_h-T_c}\}\{\frac{q_o}{k} + \frac{\ell}{2(\ell+g)} [\frac{32(\ell+g)}{\pi}]$$

$$\ell n\, [\frac{4}{1-\exp(\frac{-2\pi d}{L})}]\} \qquad (13)$$

In Equation (13) T_h-T_g is the temperature difference between the surface plates of the metering section and guard ring and T_h-T_c is the temperature difference between the hot and cold surfaces of the specimen.

III.4. Design Procedure

The formulas presented in Sections III.2 and III.3 were used to select design dimensions that would result in errors within the limits specified by the ASTM Standard.

To start the design, the sample diameter or external dimensions of the guard ring, $2(\ell+g)$ and the maximum sample thickness were assigned. The minimum thermal conductivity to be measured, the corresponding minimum temperature difference, T_h-T_c, and the sensitivity of the system used to measure and control the imbalance between the metering section and guard ring were also selected. Once the maximum total allowable error due to both edge loss and the thermal imbalance were assigned, a value of $\frac{g}{2(\ell+g)}$ which corresponded to the maximum sample thickness was determined. The total maximum allowable error is given by:

$$\varepsilon_t = \varepsilon_g + \varepsilon_e \tag{14}$$

For the design of the guarded hot plate apparatus, a sample diameter of approximately 0.126 m was selected. The maximum sample thickness was selected to be 0.0158 m and the minimum temperature difference across this sample was chosen to be 14°C. These values corresponded approximately to the 900°C/m temperature gradient recommended by the ASTM Standard. The minimum thermal conductivity to be measured was set at 0.060 W/m-°C, and the maximum total allowable error to be 1.0 percent.

Substitution of these values into Equation (9) gives a value of +0.1 percent for the edge loss error. The maximum value of the edge loss error allowed by the ASTM Standard is ±0.5 percent.

For computation of the thermal imbalance error, q_o was assumed to be given by:

$$q_o = q_{convection} + q_{radiation} + q_{conduction} \tag{15}$$

The first term in Equation (15) represents the heat exchange between the cylindrical walls of the guard ring and those of the metering section from free convection. An equation for this exchange is given by Eckert[1] to be:

$$q_{convection} = \frac{k_e A_1}{d} (T_h - T_g) \tag{16}$$

In Equation (16):

k_e is an "equivalent" thermal conductivity

d is the width of the cylindrical gap

A_1 is the mean cross sectional area of exchange

T_h is the temperature of the central surface plate

T_g is the temperature of the guard surface plate

A correlation is presented by Eckert[1] for Log (k_e/k_f) as a function of the Rayleigh Number, N_{Ra}. The Rayleigh Number is based on the layer width, d, and on the temperature difference, $T_h - T_g$. The symbol k_f represents the thermal conductivity of the gas between the cylindrical walls. The Rayleigh Number, N_{Ra}, is given by:

$$N_{Ra} = \frac{\beta g (T_h - T_g) d^3}{\nu \alpha} \tag{17}$$

In Equation (17):

β is the coefficient of thermal expansion for the fluid and is equal to $\frac{1}{T}$ for the ideal gas

g is the gravitational acceleration

ν is the kinematic viscosity of the fluid

α is the thermal diffusivity of the fluid

For air at 400°K,[1]

$\nu = 25.9 \times 10^{-6}\ m^2/s$

$\alpha = 0.3760 \times 10^{-4}\ m^2/s$

$k = 0.03365\ W/m\text{-}°C$

Substitution of these values, in addition to values for the other parameters, into Equation (17) gives a value of 0.07 for N_{Ra}. The correlation presented by Eckert gives a corresponding value of k_e/k_f of 1. Hence, the heat transport through the gas occurs by conduction only. The value of $q_{convection}$ for a 1°K imbalance is calculated to be about 0.034 Watts.

$q_{radiation}$ was estimated from:

$$q_{radiation} = \sigma F A_1 (T_h^{\,4} - T_g^{\,4}) \qquad (18)$$

In Equation (18):

σ is the Stefan Boltzman Constant = 5.729×10^{-8} $W/m^2\text{-}°K^4$

F is the shape factor between the heat exchanging areas and is 1 for the given hot plate geometry

A_1 is the area of the emitting body.

$T_h = 401°K$

$T_c = 400°K$

Substitution into Equation (18) gives a value of $\approx$ 0.045 Watts for $q_{radiation}$ for a 1°K imbalance. $q_{conduction}$ consists of the heat transport through the mechanical supports between the metering section and guard ring and that through the thermocouple and heater lead wires. These wires cross the gap at a small angle and their effective conduction length is about 0.015 m. The heat transport through the mechanical supports and lead wires for a 1°K imbalance is calculated to be 0.040 Watts. The total heat exchange between the metering section and guard ring for a 1°K imbalance is calculated to be 0.120 Watts. Substitution of this value and those of the other parameters into Equation (13) gives a value of $\varepsilon_g \approx$ 0.5 percent for a 1°K temperature imbalance. The total maximum error as given by Equation (14) is 0.6 percent. This value of ε_g is within the requirements established by the ASTM Standard. The allowable value for ε_e was verified by Equation (8) during each test.

CHAPTER IV

PHYSICAL DESIGN OF THE APPARATUS

IV.1. General

The design details of the major functional components of the guarded hot plate apparatus are described in this section. These components include the heating units, cooling units, apparatus frame, and the control and measurement instrumentation system. A "coded" isometric view of the apparatus is shown in Figure 4, and a photograph of the system components is shown in Figure 5.

IV.2. Heating Units

The function of the heating units is to provide unidirectional heat flow in the metering section of the specimen. These units consist of the metering or central heater, the guard ring heater and the cold plate heaters.

IV.2.1. Central Heater

The metering or central heater is shown in Figure 4, and consists of two copper surface plates, 1, and a central brass heater wire "former" which contains the central heater-wire, 2. The central brass heater wire former is a flat disc into which a set of concentric circular grooves was machined. A radial slot was milled at a depth equal to that of the grooves to allow the heater wire to pass between the

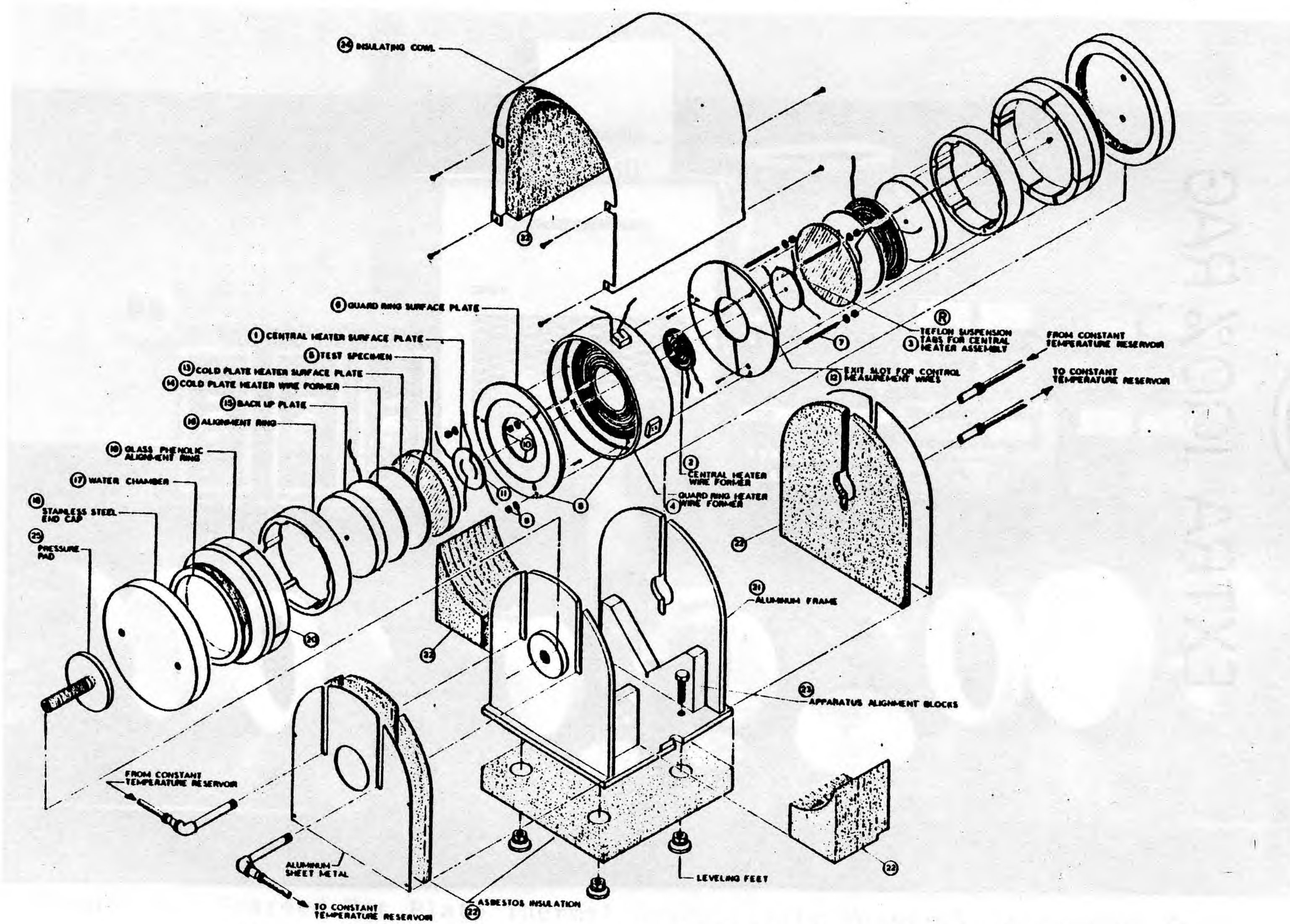

Figure 4. Guarded Hot Plate Thermal Conductivity Measuring Apparatus

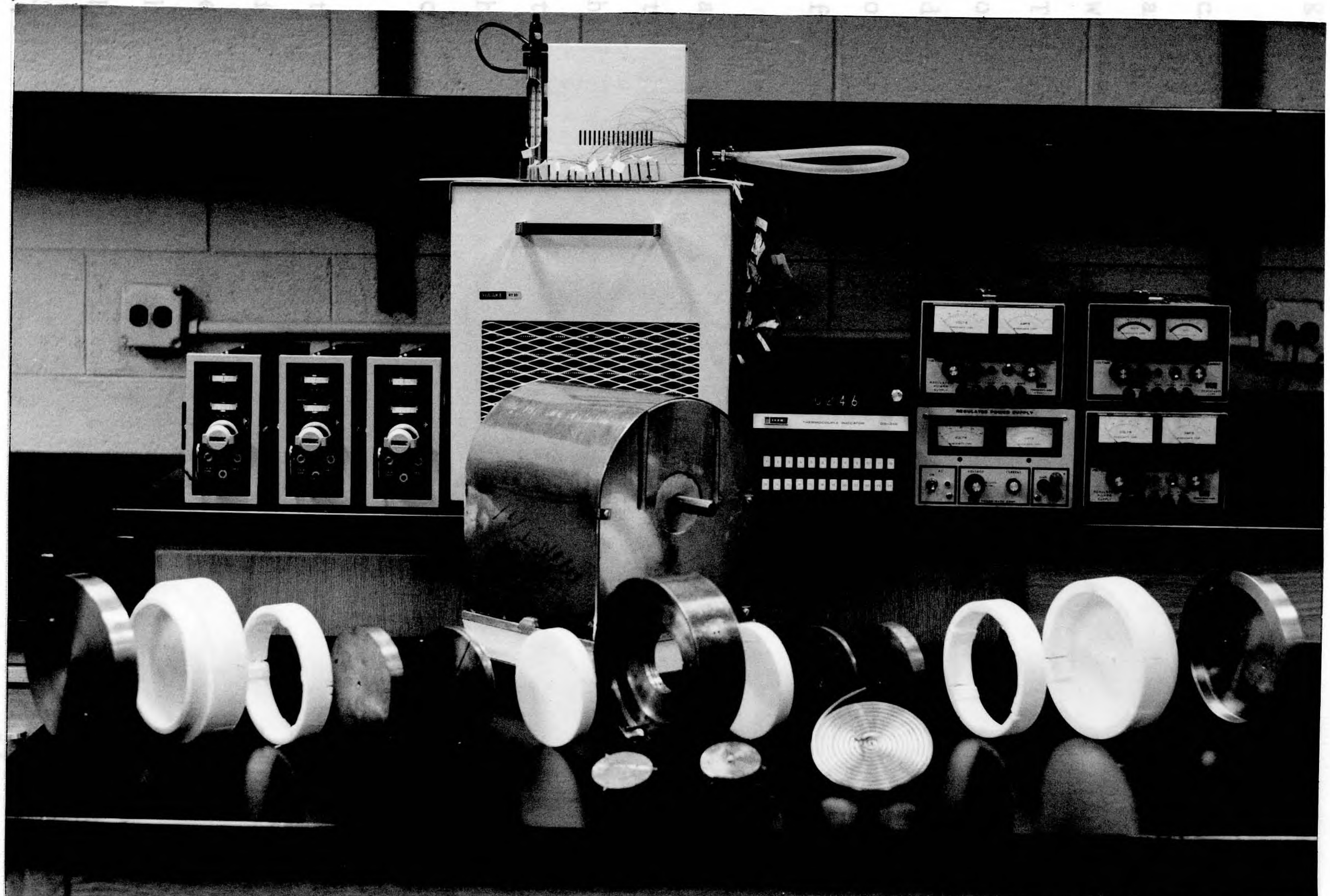

Figure 5. Guarded Hot Plate Thermal Conductivity Measuring Apparatus System.

grooves.

The heater wire was a high temperature insulated chromel thermocouple wire. The wire was 0.254 mm in diameter and has a resistance of 10.17 Ω/m. The total length of heater wire on each side of the central brass plate was 2.71 m. This corresponded to a resistance of 27.6Ω for a heater on one side of the brass plate. This length of wire was doubled and twisted together and then pressed in the grooves on each face of the brass plate. The grooves were then filled with a high conductivity heat sink compound.

Since the function of the central heater is to provide an accurately metered heat flow through the specimen, all of the energy from the power source should be dissipated into heat internal to the central heater. For this reason, the termination to the chromel wire was made inside the central heater. Copper lead wires were silver soldered to the chromel wire with an oxy-hydrogen torch.

The surface plates of the central heater were attached to the central brass plate by a threaded rod which was press fit into the heater plate and screwed into a tapped hole in each surface plate. Following assembly of the central heater, it was sanded with #400 grit sand paper on a lapping block to assure a flat surface in accordance with the ASTM Specification. The roughness height of the surface as measured by a profolometer was 4 micro inches (1×10^{-7} m). Each of the surface plates was coated with tool makers blue die in order to detect deviations from flatness. Two grooves were machined in each face of the copper surface plates to accept thermocouples. The thermocouples were constructed of 30 gauge (0.25mm diameter) copper-constantan, teflon-insulated thermocouple wire. These thermocouples were encapsulated in the grooves with copper oxide thermocouple cement (Omega Corp. Thermcoat). The plates were then resanded to reestablish flatness.

Grooves were also machined in the edges of the surface plates to accept thermocouples for measurement and control of the thermal imbalance between the guard and central sections. Three equally spaced teflon tabs, 3, were mounted on the periphery of the surface plates in order to align the central heater assembly inside the guard ring.

The capacity of the central power supply was determined by estimating the maximum amount of heat that would be necessary for any given sample. The maximum rate of heat flow required is given by:

$$q_{max} = \frac{2k_{max} A (T_h - T_c)_{max}}{L_{min}} \tag{19}$$

where:

$k_{max} \approx 0.6$ W/m-°C

$(T_h - T_c)_{max} \approx 25$°C

$A = 0.003399$ m^2

$L_{min} = 0.00635$ m

q_{max} was calculated to be 16.06 Watts. The total resistance of the central heater assembly when connected in series was 55Ω. Therefore, the central heater power supply was selected to provide current and voltage levels which could be determined from Ohm's Law:

$$q_{max} = E_{max} I_{max} = \frac{E_{max}^2}{R} = I_{max}^2 R \tag{20}$$

The value for I_{max} was calculated to be 0.54 A and E_{max} to be 29.7 V. In order to provide an adequate safety factor, a 40 volt, 2.5 ampere D.C. regulated power supply was selected. The power supply was a Power/Mate Corp. Model BPA-E-40. The input power was regulated to a stability of ±0.1 percent in accordance with the ASTM Standard.

IV.2.2. Guard Heater Assembly

The guard heater was machined from solid copper. The recessed cylindrical shell geometry of the guard ring heater wire former, 4, provided both a guard for the central heater section and for the edge of the specimen, 5. A set of spiral grooves were machined in the recessed surface of the guard ring heater, 4. The guard heater wires were placed in these grooves. They were constructed and wound in a manner similar to that described in Section IV.2.1.

The guard ring surface plates, 6, were machined from copper. These plates were attached to the recessed surface of the guard ring shell by three threaded rods, 7, which passed through clearance holes, 8, in both the guard surface plates and the recessed surface of the guard ring shell. Nuts and washers, 9, were used on both surface plates to clamp the assembly together. This design provided for the use of shims as required to assure that the guard surface plates were level with those of the central heater.

Thermocouples were mounted in grooves in the edge of guard surface plates, 10, opposite those on the edge of the central heater, 11. Four slots, 12, were milled in the underside of each surface plate to provide an exit passage for the measurement and control wires. Burrs were removed from all sharp corners to prevent accidental cutting of these wires during assembly. In addition, a recessed circular area was milled in the top side of each surface plate in order to align the test specimen.

Following assembly of the central heater section and the guard ring section, a straight edge was placed across the gap between the central section and contiguous guard. Shim stock was then used to assure that the central section was level with the guard ring within 0.000025 m.

The guard heater was designed for a power output of 125 Watts in a similar manner as described in Section IV.2.1.

IV.2.3. Cold Plate Heaters

The cold plate heaters were constructed of two pieces of copper. One piece was a flat surface plate, 13 , and the second was a heater disc, 14 , that had a spiral groove into which the heater wire was placed. Each heater was designed for a power output of 125 Watts. The surface plates were attached to the heater disc with a threaded rod arrangement. The assembly of the surface plates and heater disc was similar to that described in Section IV.2.1.

Three thermocouples were mounted in each surface plate. Two of these thermocouples were used for temperature measurement of the sample. The third thermocouple was used for temperature control of the cold plate.

A back-up plate, 15 , was located concentrically behind each cold plate heater with a dowel and hole arrangement. Two different sets of back-up plates, one made of teflon, and one made of copper were used so that the apparatus could be used over a wide temperature range.

A locating and alignment ring, 16 , was constructed to concentrically locate the floating arrangement of specimen, cold plate heater, and backup plate.

IV.3. Cooling Units

The cooling units consisted of an aluminum water chamber, 17 , a stainless steel cap, 18 , and a glass reinforced phenolic alignment ring, 19 . A neoprene gasket was used to seal the gap between the end cap and water chamber. The back-up plate and the water chamber was located concentrically with a dowel and hole arrangement. Slots, 20, were machined in the glass reinforced phenolic alignment ring to accept the threaded rods which projected through the guard ring assembly. Allowance was made for differential thermal expansion between the copper guard ring and the phenolic alignment ring.

A solution of ethylene glycol and water was circulated at constant temperature in the coolant chamber by means of a controlled reservoir/circulator. The constant temperature circulator was a Haake Corp. Model KT-33. The fluid temperature was controlled to within $\pm 0.05°C$ of the set point.

IV.4. Apparatus Frame and Housing

The apparatus frame and housing, 21, were constructed from aluminum and insulated with asbestos insulation, 22, on all sides. "Vee" blocks, 23, were welded to the frame base for alignment of the cylindrical hot plate assembly. A semi-cylindrical asbestos insulated cowling, 24, was constructed to fit over the entire assembly.

A constant reproducible pressure was applied to the heater-specimen composite by applying torque to a threaded rod which fit into a ball and socket type joint in a pressure pad, 25. Knowing the coefficient of friction between the pressure pad and the stainless steel end cap the torque required to produce a given compressive force may be calculated from:[18]

$$\tau = \frac{2}{3} \mu P r \tag{20}$$

where:

τ is the applied torque

P is the compressive force

r is the radius of the pressure pad = 0.0444 m

μ is the coefficient of friction $\approx$ 0.6.[18]

The ASTM Standard recommends a compressive stress of 2394 N/m^2. If these values are substituted into Equation (20) a value of $\tau \approx 0.6$ N-m (53 in-lb) is obtained. A torque wrench was used to reproduce this value.

IV.5. Control and Measurement System

IV.5.1. Guard/Central Section Control System

Control of the temperature imbalance between the central heater and the guard ring was achieved with a three mode temperature controller having proportional, rate, and reset adjustments. The controller was an Electronic Control Systems Corp. Model 6823. The controller was equipped with a 25 Ampere - 120 Volt power output. The controller had set point stability of ±0.01 percent/°C and a sensitivity of 0.2 microvolts. This device controlled the thermal imbalance between the central and guard sections to within ±0.1°C.

IV.5.2. Cold Plate Heater Control System

Depending upon the temperature range, the cold plate temperature could be controlled either by the constant temperature fluid or by the separate temperature controllers. The latter were to be used when cold plate temperatures above the boiling point of the heat transfer fluid were required. These temperature controllers were of the same type as used for the guard ring, the only difference being that they were not wired for differential control. Sensing was accomplished with iron-constantan thermocouples mounted in the surface plates with copper oxide cement.

IV.5.3. Temperature Measurement System

Temperature measurement was accomplished with a Doric Scientific Model DS-350-T3, 16 channel, digital thermocouple indicator. The method of verification of the accuracy of the device is described in Appendix C of this thesis. This device was used for measuring surface temperatures of the sample and for verification of the temperature imbalance between the central heater and the guard ring. Figure 6 shows the location of the thermocouples in the apparatus.

The digital indicator had an accuracy of ±0.1 percent and a sensitivity of 1 microvolt as specified by the ASTM Standard.

IV.5.4. Power Input Measurement System

The power input to the central heater was determined from voltage and current measurements. The voltage across the central heater was measured with a Hewlett Packard Model 3465A digital voltmeter having an accuracy of ±0.01 percent. The current was determined by measurement of the voltage drop

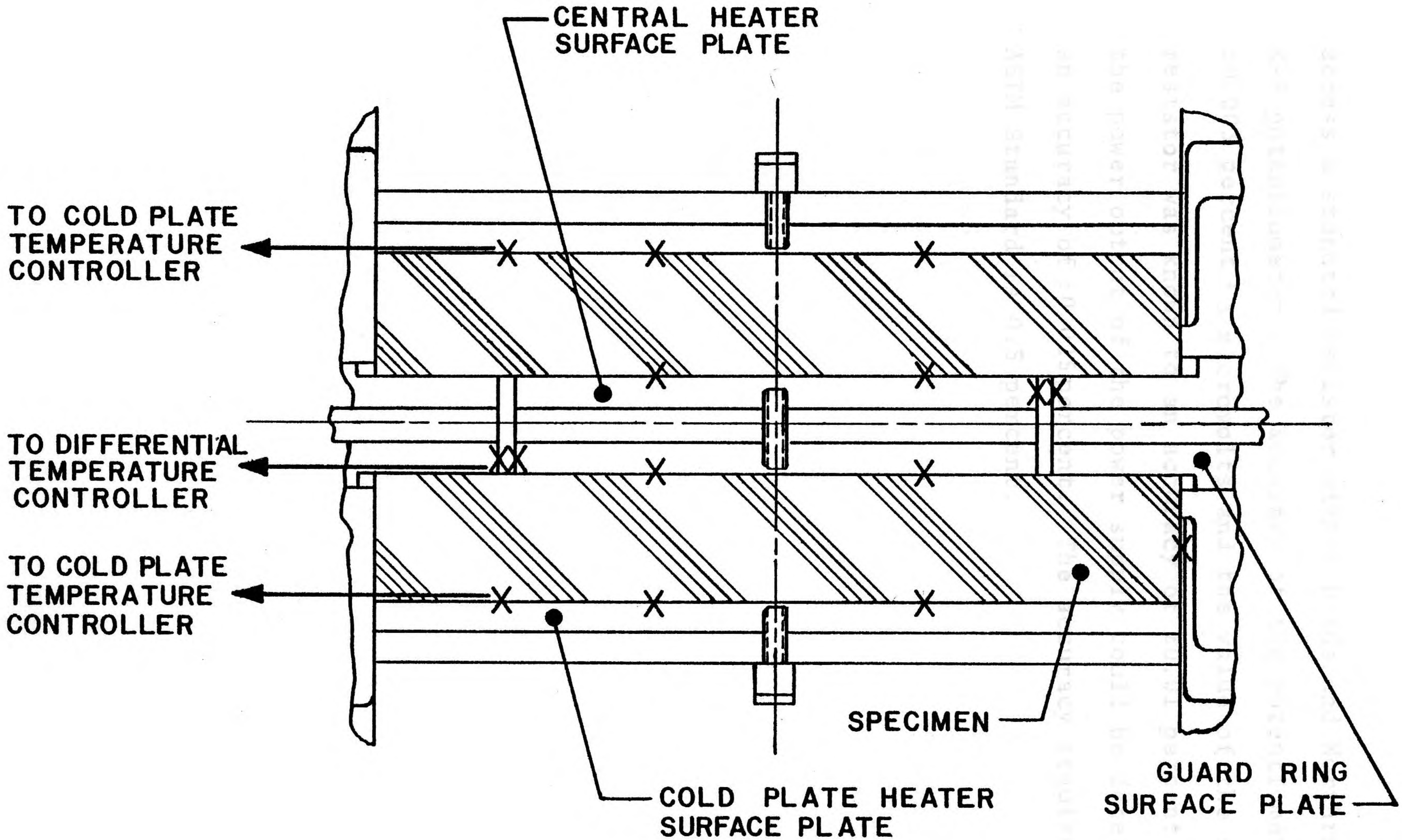

Figure 6. Thermocouple Locations

across a standard resistor with a Leeds and Northrup Type K-5 potentiometer. The accuracy of the potentiometer was ±0.003 percent + 3 microvolts and the value of the standard resistor was known to an accuracy of ±0.01 percent. Hence, the power output of the power supply could be determined to an accuracy of ±0.025 percent. The accuracy required by the ASTM Standard is 0.5 percent.

CHAPTER V

RESULTS OBTAINED

V.1. Test Procedure

Two samples, as nearly identical as possible, were prepared for each test. The samples were selected to give as accurate a representation of the material as possible. For the heterogeneous materials this was verified by measuring the density of the two specimens.

The sample size was selected to satisfy the ASTM Standard. In general, the ASTM Standard limits the maximum sample thickness, L, to 1/3 the linear surface dimension, 2ℓ, of the central heating unit; and, this value is acceptable only when the guard ring width, g, is at least equal to ℓ. These dimensions are shown in Figure 1 and are specified in order to limit the edge heat loss error.

Prior to machining, the samples were stress relieved for three hours at 120°C in a nitrogen atmosphere. The stress relief was necessary in order to minimize warpage of the samples in subsequent testing.

For those thermoplastics which did not contain fillers, or reinforcements, the specimen surfaces were sanded with #400 grit emory cloth on a lapping block to assure that the surfaces were flat to within 0.25 mm/m and parallel to within

1 percent of the sample thickness. The surfaces were coated with toolmakers blue die periodically during sanding to detect deviations from flatness.

Since all specimens tested were thermoplastics, the moisture absorption was not significant and it was certainly less than 0.5 percent. The specimens therefore were not dried as specified in Section 6.3 of the ASTM Standard. All specimens were coated with a thin film of silicone/copper flake grease to minimize the contact resistance between the heaters and the specimens.

The settings on the temperature controllers were determined by the following procedure. First, an approximate value of the thermal conductivity of the material was estimated. This approximate value, along with the recommended 900°C/m temperature gradient, was substituted into Equation (7) to determine a value for the required power input, q, to the central heater. The cold plate temperature controllers were then set to a temperature that would result in the desired mean specimen temperature. The temperature of the constant temperature bath was then set at about 5°C below that of the cold plate heaters.

When steady state was attained, the cold plate temperature controllers were readjusted so that the temperature drop across the two specimens did not differ by more than 1 percent. This requirement was met in most cases; however, occasionally the temperature drop across the two specimens differed by as much as 1.5 percent. Since an average thermal conductivity of the two specimens was computed, this difference could have only resulted in an error of 0.75 percent in the measure thermal conductivity. The average temperature of the cold plate heater units was sufficiently stable so that it did not fluctuate in any one hour test period by more than 0.5 percent of the temperature difference between the hot and cold surface plates.

The regulated power supply described in Section IV.2.1 had sufficient stability so that the average central heater surface plate temperature did not fluctuate in a one hour test period by more than 0.5 percent of the temperature difference between the hot and cold plates as required by Section 7.3 of the ASTM Standard.

Following final establishment of equilibrium, measurements were taken at thirty minute intervals on all specimens until four successive sets of measurements gave thermal conductivity values, as calculated from Equation (7) which did not differ by more than 1 percent. A sample data sheet is shown in Figure 7. It was found that the time required to attain final equilibrium was 3-4 hours utilizing the automatic control system; however, when manual control was attempted, the time required to reach equilibrium was increased to 12 hours.

Sample:____________________ Date:________________

Observers:____________________

Sample Thickness__________m

Metered Area__________m^2

Current__________Amps

Voltage__________Volts

Power__________Watts

Room Temperature__________°C

Water Temperature__________°C

$$k = \frac{qL}{A(T_h - T_c)}$$

$$\frac{qL}{A} = \_\_\_\_\_\_\_\_$$

$\overline{k}$ = ________ Watts / Meter − °C

$\overline{T}$ = ________ °C

Regulated Temperature Controller Settings: Central/Guard Differential________, Left Cold Plate________, Right Cold Plate________

Time:______		Time:______		Time:______		Time:______	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1		1		1		1	
2		2		2		2	
3		3		3		3	
4		4		4		4	
5		5		5		5	
6		6		6		6	
7		7		7		7	
8		8		8		8	
9		9		9		9	
10		10		10		10	
11		11		11		11	
12		12		12.		12	

k = _____ W/m−°C k = _____ W/m−°C k = _____ W/m−°C k = _____ W/m−°C

$\overline{T}$ = _____ °C $\overline{T}$ = _____ °C $\overline{T}$ = _____ °C $\overline{T}$ = _____ °C

Figure 7. Sample Data Sheet

V.2. Accuracy of Apparatus

The accuracy of the apparatus was estimated both theoretically and experimentally. The theoretical estimate was made by taking the total differential of Equation (6) as follows:

$$\Delta k = \frac{\partial k}{\partial L}\,\Delta L + \frac{\partial k}{\partial q}\,\Delta q + \frac{\partial k}{\partial (T_h - T_c)}\,\Delta (T_h - T_c) + \frac{\partial k}{\partial A}\,\Delta A. \qquad (19)$$

In Equation (19), ΔL, Δq, $\Delta(T_h - T_c)$, and ΔA are the uncertainties associated with the parameters in Equation (6). Substituation for the partial derivatives in Equation (19) from Equation (6) gives:

$$\Delta k = \frac{q}{(T_h - T_c)A}\,\Delta L + \frac{L\Delta q}{(T_h - T_c)A} - \frac{Lq}{A(T_h - T_c)^2}\,\Delta (T_h - T_c) + \frac{Lq}{A^2 (T_h - T_c)}\,\Delta A \qquad (20)$$

The approximate maximum values of the parameters in Equation (20) were as follows:

$$q = 2.50000 \text{ W}$$

$$\Delta q = \pm 0.000125 \text{ W}$$

$$L = 0.00952 \text{ m}$$

$$\Delta L = \pm 0.000025 \text{ m}$$

$$T_h - T_c = 15.0^\circ\text{C}$$

$$\Delta (T_h - T_c) = \pm 0.15^\circ\text{C}$$

$$A = 0.003399 \text{ m}^2$$

$\Delta A = \pm 0.000009\ m^2$

$k = 0.15\ W/m\text{-}°C$

Substitution of the above values into Equation (20) gives the following values for the various terms:

$\frac{q}{(T_h - T_c)A}\Delta L = 0.00123\ W/m\text{-}°C$ - Error due to uncertainty in measurement of specimen thickness

$\frac{L\Delta q}{(T_h - T_c)A} = 0.00002\ W/m\text{-}°C$ - Error due to uncertainty in measurement of power

$\frac{Lq\ \Delta(T_h - T_c)}{(T_h - T_c)^2 A} = 0.00467\ W/m\text{-}°C$ - Error due to uncertainty in measurement of temperature drop across specimens

$\frac{Lq\ \Delta A}{A^2 (T_h - T_c)} = 0.00124\ W/m\text{-}°C$ - Error due to uncertainty in measurement metering area

Hence a value of $\frac{\Delta k}{k}$ of 4.8 percent is obtained. In addition to this determinant uncertainty, the indeterminate uncertainty associated with the thermal imbalance and the edge heat loss was calculated in Section IV to be approximately 0.6 percent. Hence the maximum error of the apparatus is estimated to be 5.4 percent. It should be emphasized that the above estimate is a maximum and under normal circumstances this error could possibly be reduced by as much as 50 percent.

An experimental estimate of the error was obtained by measurement of the thermal conductivity of a "control" sample with three different measuring instruments by three independent sources. The three measurement methods were the ASTM guarded hot plate as described in this thesis, a thermal comparator, and an unsteady method which utilized a boiling/condensing liquid for the heat source. The control specimens were machined from a common piece of extruded sheet stock of a polytetrafluoroethylene thermoplastic. The thermal conductivity values obtained by the respective methods were 0.209, 0.270, and 0.195 W/m-°C. The value obtained with the guarded hot plate was within 7.2 percent of the average of these values. It is expected that since the thermal comparator and the "boiling liquid" instruments differed considerably in construction and measurement principles, that the data obtained with the guarded hot plate apparatus represented the most accurate value of the thermal conductivity of the "control" material.

V.3. Repeatability of Measurements

The repeatability of the apparatus was determined by conducting two sets of tests, spaced at a one month interval. In each test, data was obtained for the polytetrafluoroethylene specimens at four different temperatures. A least squares curve fit indicated that the maximum deviation from the average was less than 0.5 percent.

V.4. Materials Tested

Following verification of the accuracy and repeatability of the apparatus, three additional specimens whose values of thermal conductivities were unavailable in the literature were tested. These materials consisted of an ultrahigh molecular weight polyethylene, a 40 percent continuous glass fiber, 0.5 percent carbon black polypropylene, and a 40 percent continuous glass fiber reinforced polypropylene. The continuous glass fiber was dispersed randomly in the polypropylene specimens; hence, they were expected to have isotropic properties. All of the materials were relatively new thermoplastics of commercial importance. The ultrahigh molecular weight polyethylene specimen was machined from extruded sheet stock and the reinforced polypropylene from compression molded sheets.

The thermal conductivity of these materials as a function of temperature is illustrated in Figures 8 through 11. The data obtained are included in Appendix D of this thesis. The vertical line through each data point indicates the range of the four successive measurements required by the ASTM Standard.

The thermal conductivity as a function of temperature for these three materials as well as for the polytetrafluroethylene control specimen was found to be accurately represented by a least-squares straight line curve fit over the temperature range 0-100°C. The formulae are as follow:

A. Ultrahigh Molecular Weight Polyethylene

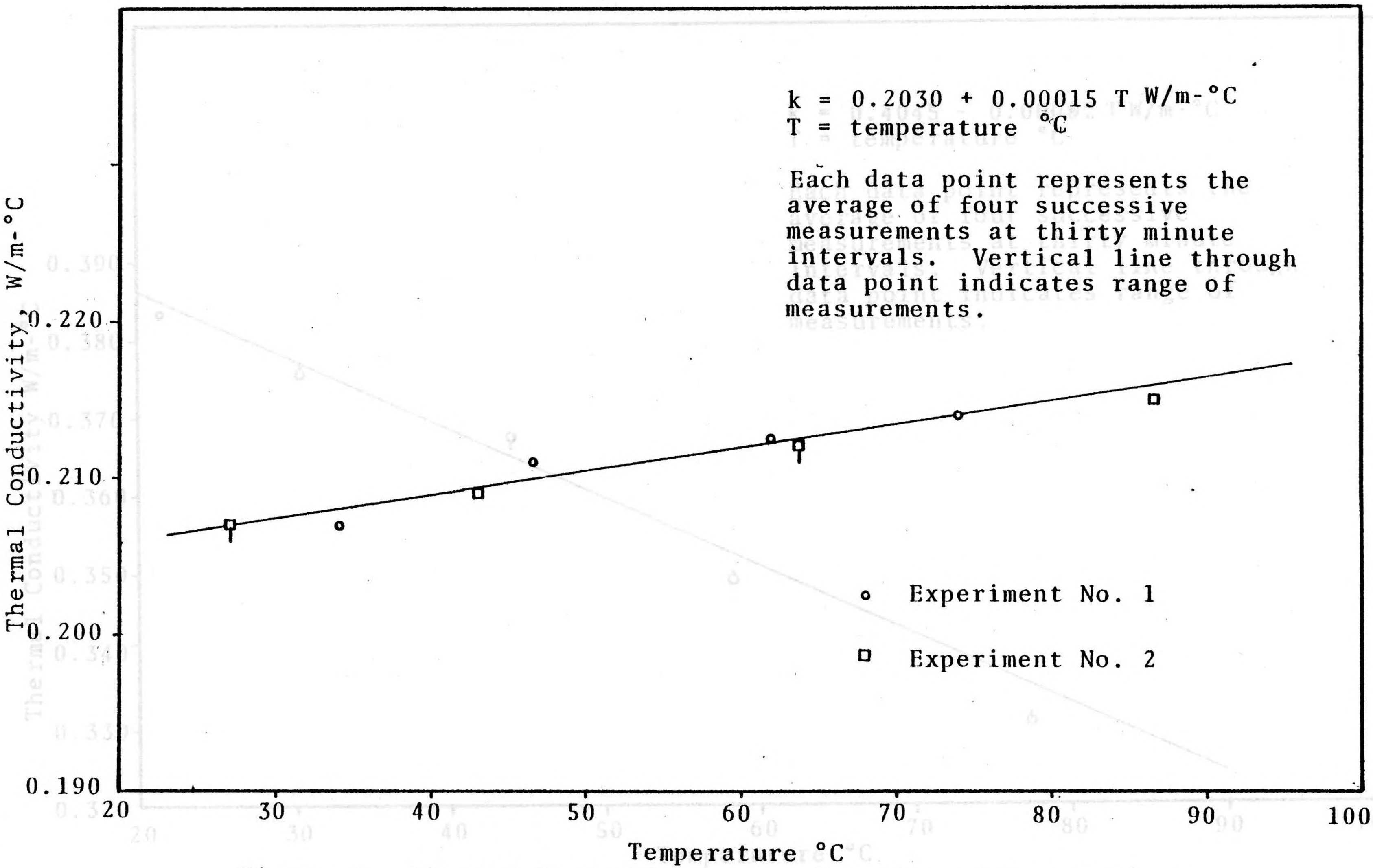

Figure 8. Thermal Conductivity as a Function of Temperature--Polytetrafluoroethylene Specimen

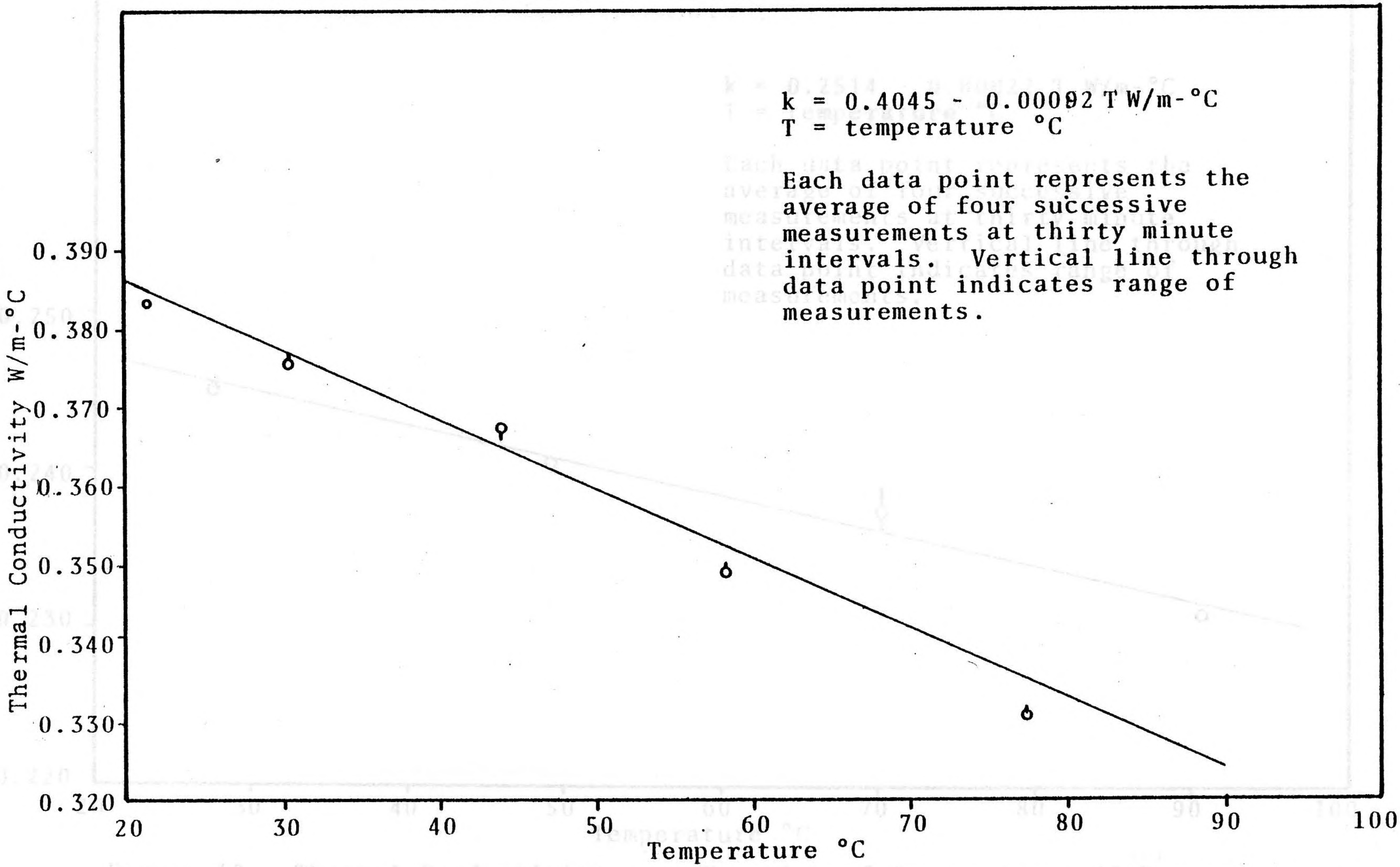

Figure 9. Thermal Conductivity as a Function of Temperature--Ultrahigh Molecular Weight Polyethylene Specimen

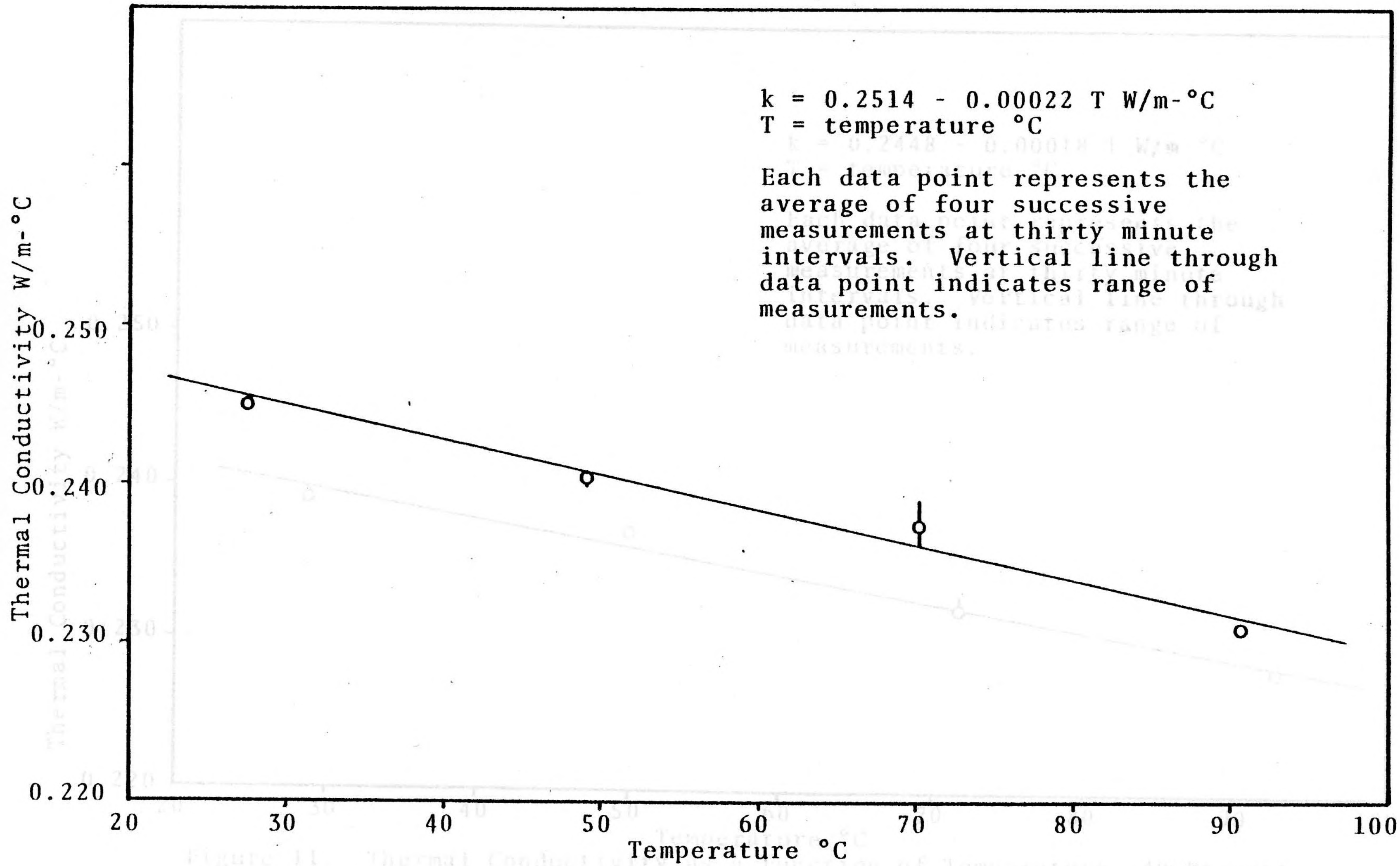

Figure 10. Thermal Conductivity as a Function of Temperature--40 Percent Continuous Glass Fiber/0.5 Percent Carbon Black/59.9 Percent Polypropylene Specimen

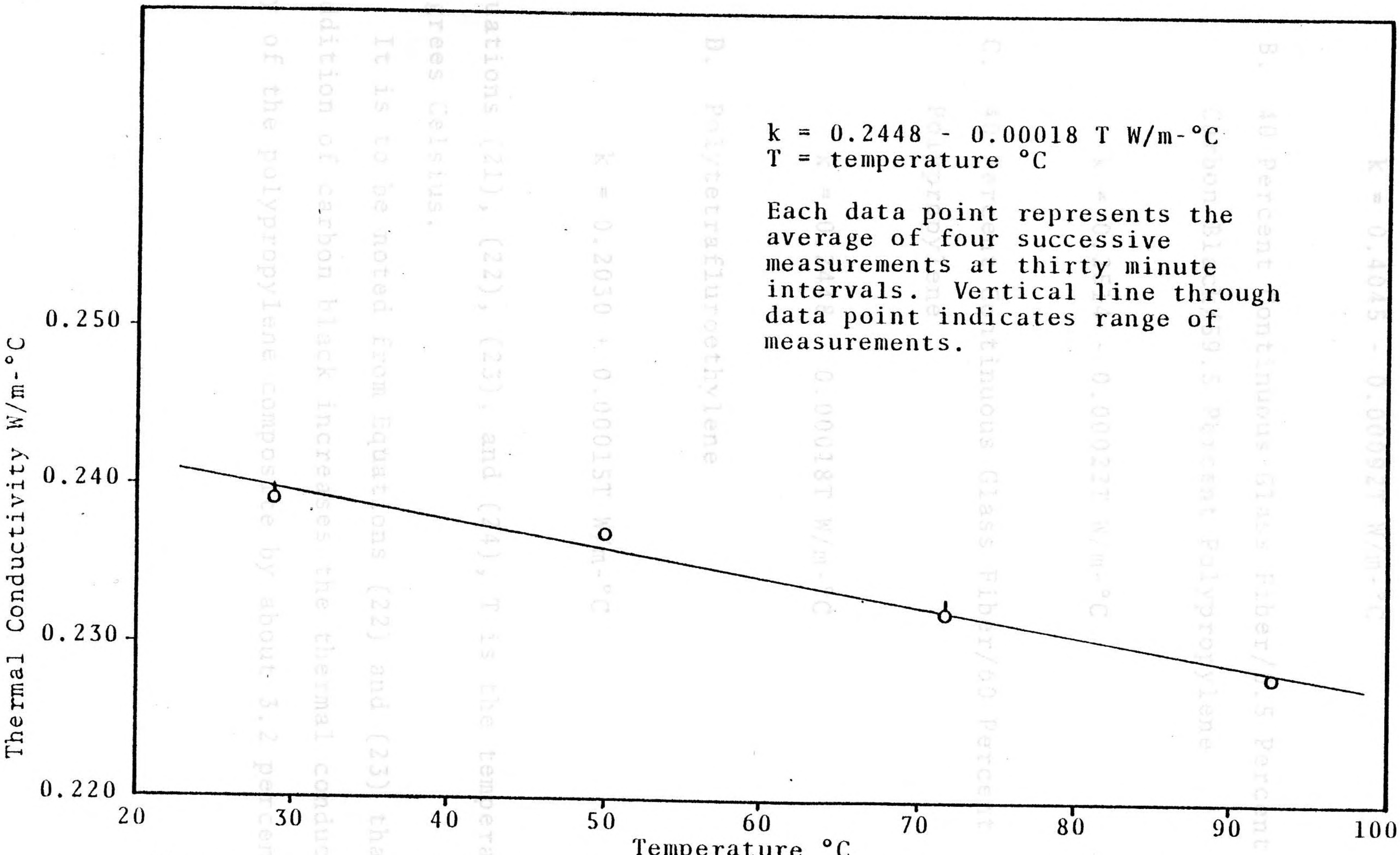

Figure 11. Thermal Conductivity as a Function of Temperature--40 Percent Continuous Glass Fiber, 60 Percent Polypropylene Specimen

$$k = 0.4045 - 0.00092T \text{ W/m-°C} \tag{21}$$

B. 40 Percent Continuous Glass Fiber/0.5 Percent Carbon Black/59.5 Percent Polypropylene

$$k = 0.2514 - 0.00022T \text{ W/m-°C} \tag{22}$$

C. 40 Percent Continuous Glass Fiber/60 Percent Polypropylene

$$k = 0.2448 - 0.00018T \text{ W/m-°C} \tag{23}$$

D. Polytetrafluroethylene

$$k = 0.2030 + 0.00015T \text{ W/m-°C} \tag{24}$$

In Equations (21), (22), (23), and (24), T is the temperature in degrees Celsius.

It is to be noted from Equations (22) and (23) that the addition of carbon black increases the thermal conductivity of the polypropylene composite by about 3.2 percent.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

VI.1. Conclusions

A guarded hot plate apparatus was designed and constructed in accordance with the ASTM C-177-71 Standard. Following the initial tests with the apparatus, it was determined that modifications to the device were required in order to improve the maintainability of the control, measurement, and power systems. Machining modifications were also necessary in order that the surface plates of all heaters would comply with the flatness requirement of the ASTM Standard. It was clearly demonstrated that the many seemingly minor requirements of the ASTM Standard are absolutely necessary for obtaining accurate and reproducible thermal conductivity measurements.

An experimental estimate of the accuracy of the apparatus was obtained by measuring the thermal conductivity of specimens machined from a common sheet of polytetrafluoroethylene plastic on three different types of measuring instruments, by three independent sources. The thermal conductivity of the specimen as determined with the guarded hot plate apparatus was 7.2 percent above the value obtained on one of the instruments and 22.6 percent below the value obtained on the other instrument. Since these instruments were not guarded hot plates, it was concluded that the value of the thermal conductivity as determined with guarded hot plate apparatus was probably the most accurate.

A theoretical estimate of the error indicated that the guarded hot plate apparatus described in this thesis is accurate to within ±5.4 percent. In addition, the measurements were verified to be repeatable to within ±0.5 percent. These results demonstrated that the ASTM C-177-71 Standard describes a method by which accurate and reproducible thermal conductivity values may be obtained for insulating materials. The thermal conductivity as a function of temperature of three plastics for which thermal conductivity data were not available in the literature was found to be accurately represented by a least-squares straight line.

VI.2. Recommendations

It is recommended that the ASTM Standard should specify, in addition to the explicit design requirements, one or more standard materials of known thermal conductivity with which the accuracy of an apparatus that is believed to have been designed to the ASTM requirements may be verified.

Also, it is recommended that if the apparatus described in this thesis were to be reproduced, that the following design changes be made:

A. All stainless steel and copper components, with the exception of the surface plates, should be constructed from a suitable aluminum alloy and yellow brass respectively. This recommendation is made in order to improve the machinability of these components.

B. A new design for the central heater and guard ring assembly should be developed so that the central heater surface plates are assured to be level with the guard ring surface plates.

C. A disconnect panel should be mounted as an integral part of the guard ring assembly so that all control, measurement, and power leads can be rapidly disconnected from the various instruments during assembly and disassembly of the apparatus.

APPENDICES

APPENDIX A

THE ASTM C-177-71 STANDARD

Designation: C 177 – 71

American National Standard Z98.1-1975
Approved Feb. 11, 1975
By American National Standards Institute

Standard Method of Test for
THERMAL CONDUCTIVITY OF MATERIALS BY MEANS OF THE GUARDED HOT PLATE[1]

This Standard is issued under the fixed designation C 177; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval.

This method has been adopted by the Department of Defense for listing in the DoD Index of Specifications and Standards. Future proposed revisions should be coordinated with the Federal Government through the Army Materials and Mechanics Research Center, Watertown, Mass. 02172.

1. Scope

1.1 This method covers the determination of the existing thermal conductivity of dry specimens of insulating, building, and other materials within the limits specified in 1.2, and the coefficients obtained apply strictly only to the particular samples as tested and for the specified thermal and environmental conditions of each test.

1.2 For practical purposes, this method is limited to determinations on specimens having thermal conductances not in excess of 60 $W \cdot m^{-2} \cdot K^{-1}$ and thickness conforming to 6.1.

1.3 Two different types of guarded hot plate apparatus are described. They are similar in principle but differ enough in construction to warrant separate descriptions for each in regard to design. The low-temperature guarded hot plate, which has metal surface plates and a definite guard gap (see 4.3), is generally used for measurements at mean temperatures such that the temperature of the cold surface may be as low as 77 K or that of the hot surface as high as 550 K. It is described in Section 4. The high-temperature guarded hot plate, which may or may not have metal surface plates and may or may not have a definite guard gap, is ordinarily used for measurements where the hot plate temperature is greater than 550 K and less than 1350 K. It is made of a cast, or otherwise formed, electrically insulating (at the highest temperature of operation) refractory material. Metal surface plates may or may not be used although they are recommended to ensure a more uniform temperature distribution on the surfaces of the plate. The high-temperature design is described in Section 5. If compliance with this method is to be reported, then all measurements made with specimen hot surface temperatures below 550 K shall be carried out using a guarded hot plate having metal surface plates and a definite guard gap. In all other respects, the method is the same for both types of apparatus. It is intended, in presenting these descriptions, to indicate the essential elements and details which experience has shown to be necessary or important for reliable measurements by this method.

NOTE 1—For the convenience of new workers in the field, detailed drawings and descriptions for the construction, and some phases of the operation, of typical hot plates complying with the requirements of this method have been made available.[2] Two of these hot plates, known as the National Bureau of Standards plate and the National Research Council plate, are metal-surfaced plates; two are high-temperature plates.

1.4 The guarded hot plate is used for determining the thermal conductivity of homogeneous materials (including those in which radiation and convection contribute to the total heat transport) in the form of flat slabs, and this method covers the procedure for such tests. It is recognized, however, that frequently it is desirable to determine the thermal conductivity of some materials in the forms in which they are used, such as molded pipe coverings, etc., or the thermal transmittance of a composite wall construction or part

[1] This method is under the jurisdiction of ASTM Committee C-16 on Thermal and Cryogenic Insulating Materials and is the direct responsibility of Subcommittee C16.30 on Thermal Measurements.

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[2] Detailed information on all of these hot plates is available at a nominal cost from the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103. Request Adjunct No. 12-301770-01.

thereof. For such purposes, ASTM Method C 335, Test for Thermal Conductivity of Pipe Insulation,[3] and ASTM Method C 236, Test for Thermal Conductance and Transmittance of Built-Up Sections by Means of the Guarded Hot Box,[3] are recommended.

1.5 For satisfactory results in conformance with this method, the principles governing the size, construction, and use of the apparatus described in this method should be followed. If the results are to be reported as having been obtained by this method, then all pertinent requirements prescribed in this method shall be met.

1.6 It is not practicable in a method of this type to aim to establish details of construction and procedure to cover all contingencies that might offer difficulties to a person without technical knowledge concerning the theory of heat flow, temperature measurement, and general testing practices. Standardization of the method does not reduce the need for such technical knowledge. It is recognized also that it would be unwise, because of the standardization of this method, to restrict in any way the further development of improved or new methods or procedures by research workers.

2. Significance

2.1 The thermal conductivity of a material (*1*) may vary due to variability of the material or samples of it, (*2*) may be affected by moisture or other conditions, and (*3*) may change with time or high temperatures. It must be recognized therefore that the selection of a typical value of thermal conductivity representative for a material, or for particular applications, if it is practically feasible, must be based on a consideration of these factors and an adequate amount of test information.

3. Symbols and Definitions

3.1 *Symbols:*

λ = thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
C = thermal conductance, $W \cdot m^{-2} \cdot K^{-1}$
R = thermal resistance, $K \cdot m^{2} \cdot W^{-1}$
q = time rate of heat flow, W
A = area measured on a selected isothermal surface, m^2
L = thickness of specimen measured along a path normal to isothermal surfaces, m
t_1 = temperature of hot surface, K
t_2 = temperature of cold surface, K

3.2 *thermal conductivity*, λ, of a homogeneous material (Note 2)—the time rate of heat flow, under steady-state conditions, through unit area, per unit temperature gradient in the direction perpendicular to an isothermal surface. For a flat slab, it is calculated as follows (Note 3):

$$\lambda = qL/A(t_1 - t_2) \tag{1}$$

NOTE 2—Materials are considered homogeneous for the purpose of this method when the value of the thermal conductivity is not affected by a change in thickness, L, or in area, A, within the range normally used. Some materials are not isotropic with respect to thermal conductivity. Care should be taken that the test method is suitable for the particular material and gives a value of conductivity applicable to the intended use.

NOTE 3—The values stated in metric units are to be regarded as the standard. Conversion factors, for thermal conductivity and thermal conductance, to other units in common use are given in Table 1.

3.3 *thermal conductance, average*, C, of a body between two definite surfaces—the time rate of heat flow between these surfaces, under steady-state conditions, divided by the difference of their average temperatures and by the area of one of the surfaces. The average temperature is one which adequately approximates that obtained by integrating the temperature of the entire surface. The thermal conductance of a flat slab is calculated as follows (Note 3):

$$C = q/[A(t_1 - t_2)] = \lambda/L \tag{2}$$

3.4 *thermal resistance*, R—the reciprocal of thermal conductance. For a flat slab, it is calculated as follows (Note 4):

$$R = 1/C = L/\lambda \tag{3}$$

4. Metal-Surfaced Hot Plate

4.1 The general features of the metal-surfaced guarded hot plate are shown schematically in Fig. 1. The plates are usually square, but round plates are sometimes used. The term "guarded hot plate" is applied to the entire assembled apparatus, including the heating unit, the cooling units, and the edge insulation. The heating unit consists of a central or metering section and a guard section. The central section consists of a central heater and central surface plates. The guard section consists of one or more guard heaters and the guard surface plates. The surface plates are

[3] *Annual Book of ASTM Standards*, Part 18.

usually made of noncorroding metal of high thermal conductivity. The working surfaces of the heating unit and cooling plates should be smoothly finished to conform to a true plane as closely as possible, and should be checked periodically. The maximum departure of the surface from a plane shall not exceed 0.25 mm/m.

NOTE 4—The planeness of the surface can be checked with a steel straightedge held against the surface and viewed at grazing incidence with a light behind the straightedge. Departures as small as 0.025 mm are readily visible, and larger departures can be measured using shim-stock or thin paper.

4.2 In the design of the guarded hot plate, consider the materials used in its construction with respect to their performance at the temperatures at which the plate will be operated. Consider also the electrical design of the heater and the design of the cooling plate to assure adequate capacity and suitable characteristics for the intended use. In all cases, design and construct the guarded hot plate so that in operation the two faces of the central section, and of the guard section, shall be substantially at the same uniform temperature, and that the heating units do not warp or depart from planeness at the operating temperatures.

4.3 Heating units shall have a definite separation or gap not greater than 3 mm between the central surface plates and the guard surface plates (Note 5). The separation between the heating windings of the central section and the contiguous guard section shall not exceed 20 mm, and this separation is allowable only if the spacing bars on either side of the separation are of a high-conductivity material such as copper, in order to distribute heat to the surface plates. In all other cases, the heater winding separation shall not exceed 3 mm. Establish the dimensions of the test area by measurements to the centers of the separations that surround this area. Paint or otherwise treat the surfaces of all plates to have a total hemispherical emittance greater than 0.8 at operating temperatures.

NOTE 5—It is recommended that the area of the gap in the plane of the surface plate be not more than 6 percent of the metering section area on that side.

4.4 Provide the guarded hot plate with a suitable means of detecting temperature imbalance between the areas of the central and guard surface plates contiguous to the separation between them. Distribute the temperature-sensing elements to register adequately (Note 6) the temperature balance existing along the length of the central section periphery. The temperature-sensing elements may be read either individually to indicate any temperature difference that may exist, or they may be connected to be read differentially to indicate such temperature difference directly. Thermocouples are generally used for this purpose, with connections arranged so that they are read as a differentially connected thermopile. The detection system shall be sufficiently sensitive to assure that variation in conductivity due to gap temperature imbalance (Note 6) shall be restricted to not more than 0.5 percent. For testing at the lower temperatures, particular caution must be used in designing for adequate sensitivity of the thermopile measurement and control system.

NOTE 6—For information on determining this requirement, see Refs (1) to (4)[4] at the end of this method.

4.5 The cooling units shall have surface dimensions at least as large as those of the heating unit including the guard heater. They shall consist of metal plates maintained at a uniform temperature lower than that of the heating unit, either by a constant-temperature fluid, or by electrical heating, or by thermal insulation of uniform conductance applied on the outermost surfaces, as appropriate for the cooling unit temperature desired.

4.6 For measuring the surface temperature of the central section of the heating unit, provide each of the central surface plates with permanently installed thermocouples set in grooves or just under the working surface. The number of such thermocouples on each side shall be not less than $5\sqrt{A}$, where A is the area in square meters of one side of the central surface plate. There shall be the same number of thermocouples permanently and similarly installed at corresponding positions in the facing cold plate. If the hot and cold plate thermocouples on each side are to be connected differentially, which is usual, they must be electrically insulated from the plates.

[4] The boldface numbers in parentheses refer to the list of references appended to this method.

4.7 Provide means (*1*) for imposing a reproducible constant pressure of the plates against the specimens to promote good thermal contact (Note 7) and (*2*) for measuring the effective thickness of the specimen to within 0.5 percent (Note 8).

NOTE 7—A steady force thrusting the cold plates toward each other can be imposed by means of a calibrated compressed spring, or a system of levers and dead weights, or an equivalent method. It is unlikely that a pressure greater than 2.5 kPa (approximately 50 lb/ft^2) on the specimens would be required; for easily-compressible specimens, small stops interposed between the corners or edges of the cold plates, or some other positive means, may be used to limit the compression of the specimens, and a constant-pressure arrangement is not needed.

NOTE 8—Because of the changes of specimen thickness possible as a result of temperature, or compression by the plates, it is recommended that specimen thickness be measured in the apparatus, at the existing test temperature and compression conditions, when possible. Gaging-points, or measuring studs at the outer four corners of the cold plates or along the axis perpendicular to the plates at their centers, will serve for these measurements. The effective combined specimen thickness is determined by the difference in the micrometered distance, or average distance, between the gaging points when the specimen is in place in the apparatus, and is not in place, and the same force is used to press the cold plates toward each other.

4.8 The best method of determining the temperature drop in the specimen depends upon its characteristics, and in some instances the choice of method is left to the judgment of the operator. For nonrigid specimens with flat uniform surfaces that conform well to the flat working surfaces of the plates, the temperature drop in specimens of thermal conductance less than 10 $W \cdot m^{-2} \cdot K^{-1}$ shall be taken as that indicated by the thermocouples permanently set in the hot and cold surface plates, and the thickness of the specimen shall be taken as the mean distance between the working surface of the hot and cold plates. For nonrigid specimens of conductance greater than 10 $W \cdot m^{-2} \cdot K^{-1}$, the operator's judgment should rule in accordance with the circumstances. Rigid specimens to be tested must, imperatively, have surfaces both flat and parallel to within 0.25 mm/m (Note 9). One method of testing rigid specimens is to install them in the apparatus with a thin sheet of suitable homogeneous material interposed between the specimen and each plate surface. This thin sheet should have a high thermal conductance relative to that of the insulating material being tested. The conductance of the composite sandwich (sheet/rigid specimen/sheet) is determined using the temperature drop indicated by the permanent thermocouples in the hot and cold surface plates. If it is not already known, the conductance of the interposed sheets alone is similarly measured in a separate test made at the same mean temperature and with the same compressive force on the plates. The conductance of the rigid specimen is then calculated from the two conductances obtained. Another method of determining the conductance of a rigid specimen is to interpose the thin layer of material between the specimen and plates as indicated above, and to determine the temperature drop across the rigid specimen by means of separate thermocouples mounted flush with, or interior to, the surface of the rigid specimen (Note 10). The number of separate thermocouples used on each side of the specimen shall be not less than $10\sqrt{A}$, where A is the area in square meters of one side of the central surface plate. If separate thermocouples are used, the effective thickness of the specimen shall be taken as the average distance, perpendicular to the face of the specimen, between the centers of the thermocouples on the two sides.

NOTE 9—A rigid specimen is one of a material too hard and unyielding to be appreciably altered in shape by the pressure of the hot and cold plates, for example, a slab of glass or hard plastic.

NOTE 10—This method of measuring the specimen temperature drop may be subject to uncertainties difficult to evaluate, among them being the effects of (*1*) distortion of heat flow lines in the immediate vicinity of the thermocouple, due to its presence, (*2*) imprecision in ascertaining the exact position of the effective thermocouple junctions, and (*3*) local inhomogeneities in the surface of the specimen at the thermocouple junctions, such as pores, voids, or inclusions.

4.9 Thermocouples mounted in the surfaces of the plates shall be made of wire not larger than 0.57 mm in diameter (No. 23 B & S gage); specimen surface thermocouples shall be made of wire not larger than 0.29 mm in diameter (No. 29 B & S gage). The thermocouples which are used to measure the temperatures of the hot and cold faces of the specimen shall be fabricated from either calibrated thermocouple wire or from wire which has been certified by the supplier to conform with ASTM Tables E 230, Temperature-Electromotive Force (EMF) Tables for Thermocouples,[8] to within the standard limits of error given in Table 15 of those tables. Thermocouples used to measure temperatures in the range from 77 to 170 K shall have a standard limit of error of ±1 percent. For information concerning sensitivity and accuracy of thermocouples in the cryogenic temperature range see Ref (5) at the end of this method.

4.10 A voltage-measuring system having a sensitivity of ±1 μV or better and an accuracy of ±0.1 percent or better shall be used for measurements of all thermocouple and thermopile emfs.

4.11 Heat losses from the outer edges of the guard section and the specimens shall be restricted by edge insulation, by governing the surrounding ambient temperature, by an additional outer guard, or by a combination of these methods. Three possible configurations that could be used to restrict edge heat losses or gains are shown in Fig. 2. A useful method of determining whether or not sufficient edge guarding or insulation is present is to measure the average temperature, T_e, at the edge of the specimen (this can be done using a thermocouple soldered or peened to a thin metal strip centered on the edge of one of the specimens). Under these conditions

$$[(T_e - T_m)/\Delta T] \leq 0.1,$$

where T_m is the mean temperature of the specimens and ΔT is the temperature difference across the specimens is a satisfactory criterion. In the first two cases shown in Fig. 2, if no guard ring perimeter heater is used, the required minimum thermal resistance of the edge insulation, on the basis that the total edge heat loss shall not exceed one fifth of the heat flow through the two specimens, is given by the following equation:

$$R = 5x/S\lambda\,[(4x + 2y)(T_m - T_a)/\Delta T + y]$$

where:

x = thickness of each specimen, m,
y = thickness of the heating unit, m,
S = length of the side (or diameter) of the guard section, m,
λ = thermal conductivity of the specimens, $W \cdot m^{-1} \cdot K^{-1}$,
T_m = mean temperature of the specimens, K,
T_a = temperature of the outer surface of the edge insulation, K, and
ΔT = temperature difference across the specimens, K.

It should be noted that R depends on both $(T_m - T_a)$ and ΔT, and also that since it is desirable that the net heat transfer from the outer edges of the specimens should be kept nearly equal to zero, $(T_m - T_a)$ should be kept small.

NOTE 11—For information on calculating the effects of edge losses, see Refs (4) and (6) to (8).

4.12 A cabinet or enclosure surrounding the guarded hot plate, and equipped for maintaining the desired interior air temperature and dew point, is recommended for use in tests conducted at mean temperatures differing substantially from the laboratory air temperature.

5. High-Temperature Hot Plate

5.1 The general features of the high-temperature guarded hot plate are shown schematically in Fig. 3. The plate may be a round or square configuration. If a square plate configuration is used, it is recommended that separate independently controlled guard heaters be provided to allow for the additional heat losses which occur at the corner regions. The term "guarded hot plate" is applied to the entire assembled apparatus including the heating units, the cooling units, and the insulation. The heating units consist of (1) a central or metering section, (2) a guard section that must be either a double guard heater, with the outer guard section having a width equal to or greater than one half of the inner primary guard width, or a primary guard heater with an outer cylindrical guard extending over the length of the composite sample stack, (3) additional corner heaters (for square configuration only), and (4) cold surface heaters. If metal surface plates are used, they should be of a suitable noncorroding metal of as high a thermal conductivity as possible. Physical separation of the central and inner guard areas is to be preferred if associated problems of alignment and flatness of the plates are minimized by suitable design. All heaters should be capable of being adjusted to any desired temperature level within the limits specified in 1.3. The

[8] *Annual Book of ASTM Standards*, Part 44.

cooling units normally consist of two liquid-cooled heat sinks with an adequate layer of insulation between them and the adjacent cold surface heater. An additional outer peripheral liquid-cooled shroud is recommended (see 5.11). The working surface of the heating units and cooling plates shall be finished smoothly to conform to a true plane as closely as possible and should be checked regularly. The maximum departure of the surface from a plane shall not exceed 0.25 mm/m (Note 4). The refractory material plates should have a thermal expansion not greater than 1 percent of the linear surface dimension of the hot plate. This expansion shall be computed from the difference between the length measurements taken at maximum use temperature and at room temperature.

5.2 In the design of the high-temperature guarded hot plate, give due consideration to obtaining satisfactory performance at the temperatures at which the plate will be operated. Consider also the electrical design of the heaters and the design of the cooling plates to assure adequate capacity and suitable characteristics for the intended use. The refractory plate composition should have adequate electrical resistance at the maximum use temperature to prevent possible power exchange between adjacent heating circuits embedded within the refractory material. The maximum permissible power exchange shall be 0.5 percent of the test area power consumption at the particular test temperature. In all cases great care should be taken to ensure that there will be no compatibility problems between the test specimens and the materials used in the construction of the plates for the temperature and environment conditions of a specific measurement. In all cases, design and construct the guarded hot plate so that in operation the two faces of the central section, and of the guard section, shall be substantially at the same uniform temperature, and that the heating units do not warp or depart from planeness at the operating temperatures. The surfaces facing both sides of the test specimens should be treated so that they have a total hemispherical emittance at the operating temperatures of no less than 0.7 and preferably much higher.

NOTE 12—At high temperatures the importance of high emittance of the surfaces adjacent to the specimens cannot be stressed too strongly since the radiative heat transfer predominates as the temperature increases.

5.3 In a high-temperature plate having a gap between the central and guard areas, the gap shall not exceed 2 mm (Note 5). The gap between the central and guard areas shall be filled with a thermally and chemically compatible high-temperature insulation to avoid radiative heat transfer across the gap. The effective metering area of the high-temperature plate is determined by the positions of the potential taps used to evaluate the power input to the metering area winding.

NOTE 13—For a double-spiral (bifilar) winding with the spacing between wires equal to b, and with the potential taps for the metering section in effect at points on the wires at the ends of a diameter $2a$ (or for a single-spiral winding of spacing b with the potential taps in effect at the center and at a radius a), the effective metering area is equal to

$$\pi a^2[1 + (1/12)(b/a)^2]$$

5.4 Provide the guarded hot plate with a suitable means for detecting temperature imbalance between the central and guard sections of the plate. Distribute the temperature-sensing elements to register adequately (Note 6) the temperature balance existing between the outer edge of the metering area and the inner edge of the guard section. Locate the thermocouple junctions used for detecting temperature imbalance at the edge of the metering area on the same radius, and distant from the edge of the metering area by not more than one quarter of the guard width. The temperature-sensing elements may be read either individually to indicate any temperature difference that may exist, or they may be connected to read differentially to indicate such temperature difference directly. The detection system shall be sufficiently sensitive to assure that variation in conductivity due to temperature imbalance (Note 6) between the central and guard sections shall be restricted to not more than 0.5 percent. Thermocouples should be fixed on the edge of each test specimen at the center position (see 4.11).

5.5 The cold-surface heaters shall have surface dimensions at least as large as those of the combined central and guard sections of the hot plate. They shall consist normally of a flat single heater and refractory formers with or without metal surface plates, maintained at a uniform temperature lower than that of the main hot plate.

5.6 Permanently installed thermocouples to be used in determining the temperature difference across the specimen shall be set flush with the working surfaces, and shall number not less than $5\sqrt{A}$ on each working surface, where A is the area in square meters of the metering area of the hot plate on one side. However, permanently installed thermocouples are not mandatory if the temperature difference across the specimen is to be determined by means of separate thermocouples (see 4.8).

5.7 Means shall be provided (*1*) for imposing a reproducible constant load upon the system to promote good thermal contact (Note 7) and (*2*) for measuring the effective thickness of the specimen to within 0.5 percent (Note 8). Thickness measurement *in situ* at the temperature of test is necessary or must be reliably calculated if an accurate thermal conductivity value is to be obtained. Furthermore, due care should be taken to measure the thickness before and after the test has been completed in order to check for irreversible changes.

5.8 The best method of determining the temperature drop in the specimen depends on the circumstances, and is therefore left to the best judgment of the operator. One method often used is to attach separate thermocouples on a sheet of asbestos paper or other suitable material, and to interpose the sheet between the specimen and the adjacent working surface of the apparatus, with the thermocouples in contact with the specimen. For rigid and hard specimens (Note 9), which should be flat to within 0.25 mm/m, it may be important to set the separate thermocouples in tight grooves in the faces of the specimens. The number of separate thermocouples used, at each face of the specimen, shall be not less than $10\sqrt{A}$, where A is the metering area in square meters of one side of the hot plate. If separate thermocouples are used, take the effective thickness of the specimen as the average distance, perpendicular to the face of the specimen, between the centers of the thermocouples on the two sides. Another method, feasible if a suitable resilient sheet material is available for the test temperatures in question, is to use the composite sandwich (sheet/specimen/sheet) technique described in 4.8, in which permanently installed thermocouples in the plates are used.

NOTE 14—This method automatically compensates for any effective or virtual thermal resistance between the positions where the permanently installed plate thermocouples are located and the plate working surface. Such resistance may be appreciable in the case of a high-temperature plate.

5.9 Thermocouples mounted in the surfaces of the plates shall be made of wire not larger than 0.64 mm in diameter (No. 22 B&S gage); specimen surface thermocouples shall be made of wire not larger than 0.46 mm in diameter (No. 25 B&S gage). The thermocouples that are used to measure the temperatures of the hot and cold faces of the specimen shall be fabricated from either calibrated thermocouple wire or from wire that has been certified by the supplier to conform with Tables E 230 to within the standard limits of error given in Table 15 of those tables.

5.10 A voltage-measuring system having a sensitivity of $\pm 1\ \mu V$ or better and an accuracy of ± 0.1 percent or better shall be used for measurements of all thermocouple and thermopile emf's.

5.11 To reduce heat losses from the outer edges of the composite test section, the assembly shall be surrounded by a coaxial cylindrical container of suitable material of internal diameter at least twice the diameter of the stack assembly. The interspaces and surrounds shall be filled with a suitable insulation within distance of somewhat greater than the axial length between the outermost surfaces of the heat sinks.

NOTE 15—Extreme care should be taken to ensure that no voids, gas pockets, or other extraneous sources of high-temperature radiative heat transfer can occur at or near the test section.

6. Test Specimens

6.1 Prepare two specimens from each sample. They shall be as nearly identical as possible, of such size as to completely cover the heating unit surfaces, and shall be of sufficient thickness to give a true average representation of the material to be tested. The relationship between the thickness of the test specimen used and the dimensions of the guarded hot plate shall be as follows:

Maximum Thickness of Test Specimen, mm	Minimum Linear Surface Dimensions of Guarded Hot Plate (Square or Round), mm	
	Central Section of Heating Unit	Width of Guard Area Around Heating Unit
33	100	50
50	150	75
75	225	113
100	300	150

6.2 In testing all forms of homogeneous materials, make the surfaces of the test specimens as plane as possible, by sandpapering, face-cutting in a lathe, grinding, or otherwise, so that intimate contact between the specimens and the plates or interposed sheets can be effected. For rigid materials, make the faces of the specimens flat to within 0.25 mm/m and parallel, within the total plate area, to within 1 percent of the sample thickness.

6.3 When testing homogeneous solid or blanket-type materials, prepare the specimens in accordance with 6.1 and 6.2. Determine their weight before and after they have been dried to constant weight in a ventilated oven at a temperature from 375 to 395 K (Note 16). From these weights calculate the percentage as-received moisture. Promptly after drying and weighing, place the specimens in the apparatus taking care to prevent loss of material or moisture gain. Determine the as-tested thickness and volume by measurements made preferably at the end of the test under conditions of test-temperature equilibrium, and from these data and the dry weight, calculate the as-tested density. If it is feasible to do so with good thermal contact between the plates of the apparatus and the specimens, test blanket- or batt-type material at approximately the thickness and density determined by ASTM Methods C 167, Test for Thickness and Density of Blanket- or Batt-Type Thermal Insulating Materials[3] (Note 7).

NOTE 16—If the material may be adversely affected by heating to 375 K, dry it in a desiccator at a temperature of approximately 330 K.

6.4 When testing loose-fill materials, take a representative portion slightly greater than the amount needed for the test from the sample. Weigh this material before and after it has been dried to constant weight in a ventilated oven at a temperature from 375 to 395 K (Note 16). From these weights, calculate the percentage as-received moisture. Then weigh out an amount of the dried material such that it will produce two specimens of the desired as-tested density using either Method A or B, given in the Appendix. As the volume of the specimen space is known, the required weight can be determined. During placement, take care to prevent loss of the weighed material, or significant moisture gain. When Method A is used, or Method B with covers of insignificant thermal resistance, take the specimen surface temperatures as equal to those of the surfaces of the hot and cold plates.

7. Procedure

7.1 For any test, adjust the temperature difference between the hot and cold surfaces of the specimens to not less than 5 K. It is recommended that for good insulators, the temperature gradient in the specimen be 900 K/m or more.

7.2 When thermal conductivity values are desired for the situation where the specimen is immersed in air (or some other gas), adjust the atmosphere surrounding the guarded hot plate during a test to a dew-point temperature 5 K or more lower than the cold-plate temperature. For operation at cryogenic temperatures, this shall require purging the system with dry gas prior to cooling the apparatus. Between 77 and 230 K, use dry nitrogen gas, rather than air as the atmosphere and contain the apparatus in a sealed system. At cold-plate temperatures below 125 K, take care to adjust the nitrogen pressure so as to avoid condensation. When thermal conductivity values are desired for the situation where the specimen is *in vacuo*, evacuate the system prior to cooling.

7.3 Supply the heating element of the central heater with electrical energy for heating it, providing for the measurement of the average rate of heat generation therein to an accuracy of not less than 0.5 percent. Automatic regulation of the input power is recommended; in any case, fluctuations or changes in input power shall not cause the temperature of the hot-plate surfaces to fluctuate, or to change in 1 h of a test period, by more than 0.5 percent of the temperature difference between the hot and cold plates. Measure the input power in such a way that the average power input during a test period can be determined; if the power input is of a fluctuating kind, make an integrated energy measurement. Adjust and maintain the power input to the guard section, preferably by automatic control, so as to effect the degree of temperature balance between the central and guard heater sections that is required for conformance to 4.4 or 5.4. For measurements at high temperatures, adjust the power to the outer guard or cylindrical guard heater, preferably by automatic control, so as to effect, for the test specimen, that the degree of temperature balance between the center of the outer edge and the mean temperature conform to the conditions given in 4.11.

7.4 Adjust the cooling units or cold surface heaters so that the temperature drops through the two specimens do not differ by more than 1 percent. The temperatures of the cooling plates or cold surface heaters, in the case of the high-temperature plate, during a test period shall not fluctuate or change, in 1 h, by more than 0.5 percent of the temperature difference between the hot and cold surfaces of the specimen.

7.5 Determine the temperature difference across the specimens, the hot- and cold-plate temperatures, the center-to-guard temperature balance, and the electrical power input to the central section.

7.6 In order to attain the thermal conductivity value, it is essential to allow sufficient time for the apparatus and specimens to attain thermal equilibrium. The time required will depend on the specific apparatus, the control system and its operation, the test temperatures, and on the thermal diffusivity and thickness of the specimens. The observations listed in 7.5 should be made at intervals of not less than 30 min, until four successive sets of observations give thermal conductivity values differing by not more than 1 percent.

NOTE 17—Particularly in low temperature measurements on good insulators having low thermal diffusivities, the internal temperatures of the specimens can require a very long time to attain thermal equilibrium so that it is possible to have four consecutive 30-min tests which yield thermal conductivity values within 1 percent of each other and still not have steady-state conditions. Sufficient time must be allowed for the internal temperatures of the insulation to stabilize. For further discussion of this problem, see Ref (9).

7.7 Particular care is indicated if a guarded hot plate is used for measurements under vacuum conditions. If a hard vacuum is desired, materials must be carefully selected to avoid excessive outgassing. Under vacuum conditions, especially at lower temperatures, serious errors can arise if due care is not taken in installing heater and thermocouple leads so as to minimize extraneous heat flows and temperature measurement errors. Vacuum operation can greatly increase the time required for the apparatus and specimen to reach thermal equilibrium (due to outgassing of the apparatus and specimens and to the lower thermal diffusivity of the specimens).

7.8 Upon completion of the observations in 7.5, measure the thickness of the specimens (see Section 4.8 and Note 8) for use in calculating the final results, and determine the weight of the specimens or of the test material in the specimens immediately.

8. Calculations

8.1 Calculate the density of the dry specimen as tested, D, the as-received moisture content of the material, M, and the moisture regain of the specimen during test, R_w or R_v, as follows:

$$D = W_2/V$$
$$M = [(W_1 - W_2)/W_2] \times 100$$
$$R_w = [(W_4 - W_3)/W_3] \times 100$$
$$R_v = [(W_4 - W_3)/1000\ V] \times 100$$

where:

D = density of the dry material as tested, kg/m³,

M = moisture content of the material as received, dry weight percent,

R_w = moisture regain of material during test, dry weight percent,

R_v = moisture regain of material during test, dry volume percent,

W_1 = weight of material in as-received condition, kg,

W_2 = weight of material after drying, kg,

W_3 = weight of dry material in specimens, kg,

W_4 = weight of material in specimens immediately after test, kg, and

V = volume occupied by material in specimens during test, m³.

8.2 Calculate thermal conductivity (or conductance) by means of Eq 1 (or 2) (3.2 and 3.3), using average values of the observed steady-state data.

9. Report

9.1 The report of the results of each test shall include the following (the numerical values reported shall represent the average values for the two specimens as tested):

9.1.1 Name and any other pertinent identification of the material,

9.1.2 Thickness of the specimen (or material) as tested, m,

9.1.3 Method and temperature of drying,

9.1.4 Density of the dry material as tested, kg/m^3,

9.1.5 As-received moisture content of the material, dry weight percent,

9.1.6 Moisture regain of the material during test, dry weight percent or volume percent, or both,

9.1.7 Average temperature gradient in the specimen during the test as computed from the temperatures of the hot and cold faces for the specific data point, K/m,

9.1.8 Mean temperature of test, K,

9.1.9 Heat flux through each specimen during test, W/m^2,

9.1.10 Thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$, or thermal conductance of specimen, $W \cdot m^{-2} \cdot K^{-1}$,

9.1.11 Orientation of the plane of the specimen: vertical or horizontal,

9.1.12 For tests made using sheet material interposed between the specimen and the plate surfaces, give information as to the nature, thickness, and thermal conductance of the sheet material. If separate thermocouples were used to determine the temperature drops in the specimens, also give information as to the size of the thermocouples, the method of affixing them to the specimen, and the measured distance between their centers,

9.1.13 Where appropriate to the condition and temperature of the test, the approximate resistance of the edge insulation and the ambient temperature surrounding the plate during the test, and also the duration of the measurement portion of the test, and

9.1.14 The vacuum reading or type and pressure of purge gas surrounding the specimen.

9.2 Include a graphical representation of the results in the report when pertinent. This shall consist of a plot of each value of thermal conductivity obtained versus the corresponding test mean temperature, plotted as ordinates and abscissas, respectively.

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(6) Somers, E. V., and Cyphers, J. A., "Analysis of Errors in Measuring Thermal Conductivity of Insulating Materials," *Review of Scientific Instruments*, Vol 22, 1951, pp. 583–586.

(7) Woodside, W., "Analysis of Errors Due to Edge Heat Loss in Guarded Hot Plates," *Symposium on Thermal Conductivity Measurements and Applications of Thermal Insulations, ASTM STP 217*, ASTTA, Am. Soc. Testing Mats., 1957, pp. 49–64.

(8) Woodside, W., "Deviations from One-Dimensional Heat Flow in Guarded Hot Plate Measurements," *Review of Scientific Instruments*, Vol 28, 1957, pp. 1933–1937.

(9) Pratt, A. W., "Analysis of Error Due to Edge Heat Loss in Measuring Thermal Conductivity by the Hot Plate Method," *Journal of Scientific Instruments*, Vol 39, 1962, pp. 63–68.

(10) *Thermal Conductivity Measurements of Insulating Materials at Cryogenic Temperatures, ASTM STP 411*, ASTTA, Am. Soc. Testing Mats., 1967.

APPENDIX B

FUNCTIONAL SPECIFICATION OF THE GUARDED HOT PLATE APPARATUS

I. General: Meets ASTM C-177-71 for measurement of thermal conductivity of solid insulating materials. Sample and central heater guarded with automatically controlled heater unit, and two automatically controlled cold plate heaters.

II. Sample:

A. Size: 12.78 cm in diameter; 0.76 cm to 2.54 cm thick.

B. Thermal Conductivity Range: 6×10^{-2} W/m-°C to 0.6 W/m-°C.

III. Temperature Range: -26°C to +275°C

IV. Accuracy: ±5.4 percent

V. Repeatability: ±0.5 percent

VI. Time for Single Measurement from "Cold" Start-Up: 3-4 hours

APPENDIX C

THERMOCOUPLE CALIBRATION PROCEDURE

The ASTM Standard does not require that the thermocouples be calibrated if the thermocouple wire is certified by the manufacturer to conform to the ASTM Tables E-230. However, it was believed desirable to do so in this thesis in order to verify the accuracy of the digital readout system. The method of calibration was accomplished by direct comparison of the digital readout from the thermocouples to that of a mercury in glass thermometer certified by the National Bureau of Standards to an accuracy of ±0.1°C. A schematic of the calibration arrangement is shown in Figure C-1. The arrangement consisted of a bank of sixteen thermocouples immersed in a constant temperature bath which was controlled to within ±0.01°C of the set point. Two NBS certified thermometers were immersed in the bath and their readings were corrected for stem depth immersion. The digital readout of the temperature indicated by the thermocouples was plotted as a function of the NBS thermometer readings. The data are given in Table C-1 and the corresponding calibration curve in Figure C-2.

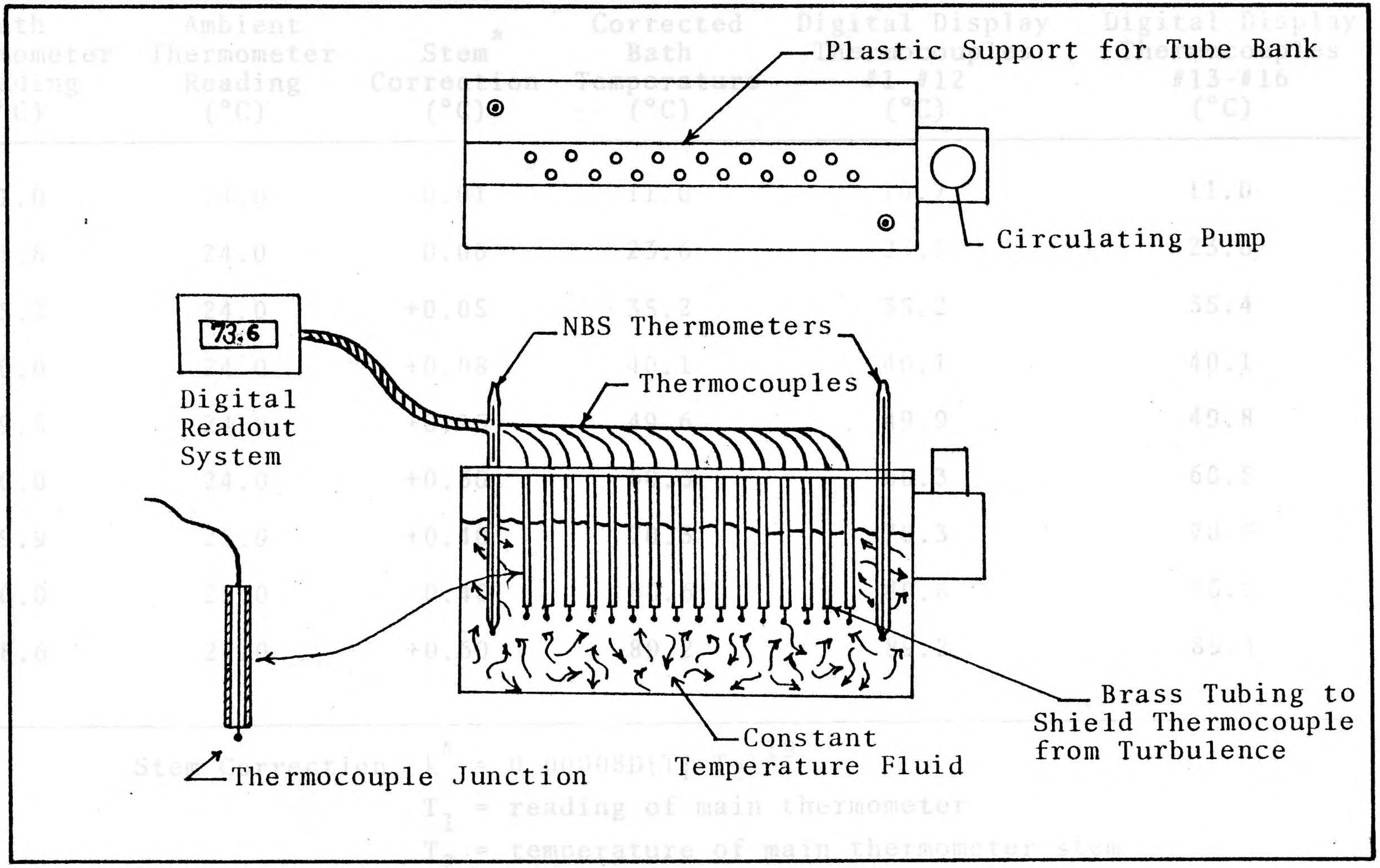

Figure C-1. Thermocouple Calibration Arrangement

Table C-1. Calibration Data for Digital Thermocouple Display

Bath Thermometer Reading (°C)	Ambient Thermometer Reading (°C)	Stem* Correction (°C)	Corrected Bath Temperature (°C)	Digital Display Thermocouples #1-#12 (°C)	Digital Display Thermocouples #13-#16 (°C)
11.0	24.0	-0.01	11.0	10.7	11.0
23.6	24.0	0.00	23.6	23.5	23.6
35.2	24.0	+0.05	35.2	35.2	35.4
40.0	24.0	+0.08	40.1	40.1	40.1
49.5	24.0	+0.15	49.6	49.9	49.8
60.0	24.0	+0.30	60.3	60.3	60.5
69.9	25.0	+0.40	70.3	70.3	70.5
80.0	25.0	0.40	80.6	80.6	80.8
88.6	24.0	+0.60	89.2	89.2	89.4

Stem Correction, $k^* = 0.00008D(T_1 - T_2)$[19]

T_1 = reading of main thermometer

T_2 = temperature of main thermometer stem

D = no. of degrees of exposed filament

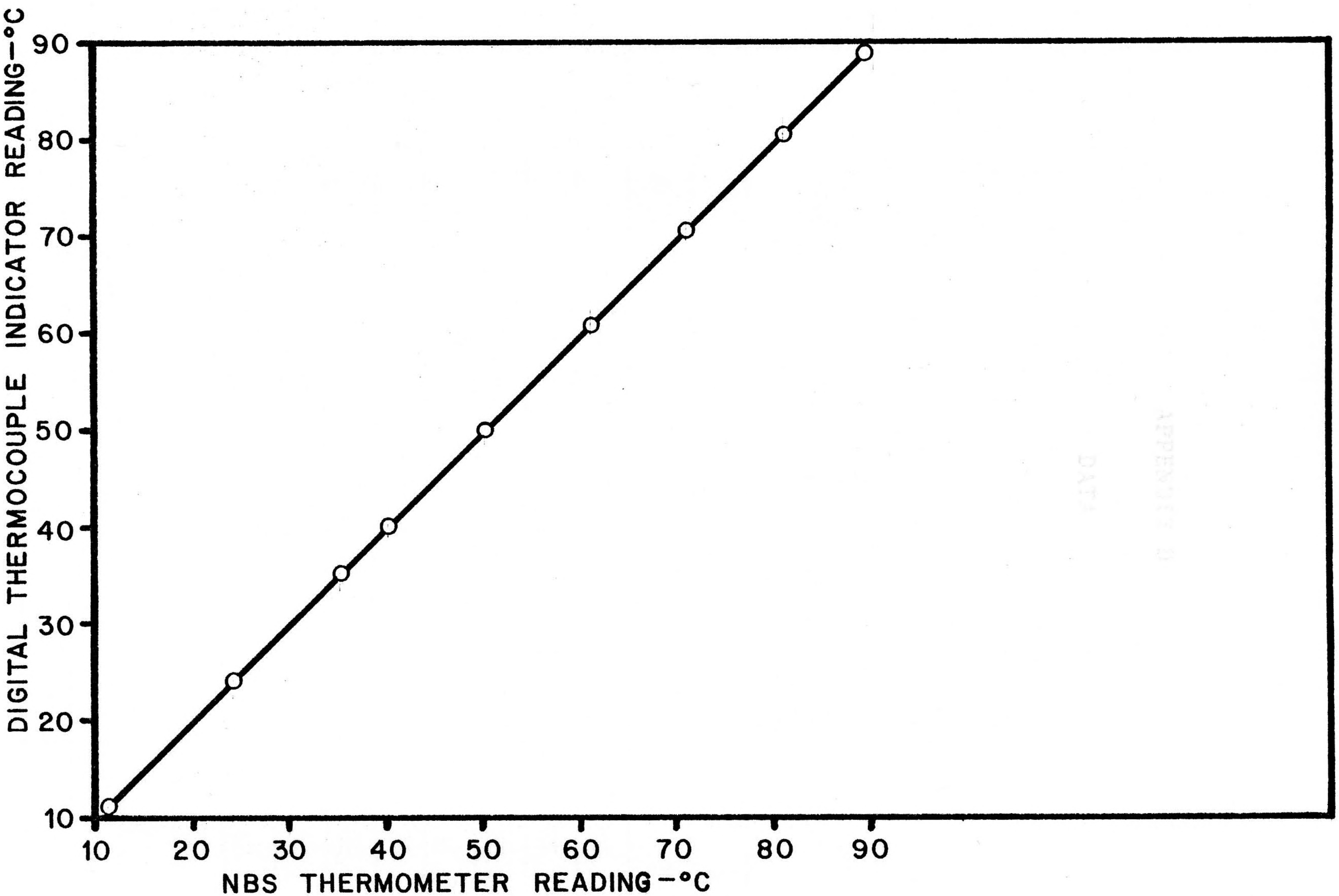

Figure C-2. Calibration Curve for Digital Thermocouple Indicator

APPENDIX D

DATA

Sample: Polytetrafluoroethylene Date: 5/26/76

Observers: K. W. Jackson

Sample Thickness 0.00772 m

Metered Area 0.003399 m^2

Current 0.244351 Amps

Voltage 17.205 Volts

Power 4.20406 Watts

Room Temperature 26.0 °C

Water Temperature 0.0 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 4.77425

$\overline{k}$ = 0.214 Watts/Meter − °C

$\overline{T}$ = 74.0 °C

Regulated Temperature Controller Settings: Central/Guard Differential 23.0, Left Cold Plate 146.8, Right Cold Plate 146.8

Time: 5:50		Time: 6:20		Time: 6:50		Time: 7:30	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	85.1	1	85.2	1	85.0	1	85.1
2	85.1	2	85.4	2	85.0	2	85.1
3	85.2	3	85.1	3	85.2	3	85.3
4	85.2	4	85.1	4	85.2	4	85.2
5	75.1	5	75.1	5	75.0	5	75.1
6	85.2	6	85.3	6	85.1	6	85.1
7	85.2	7	85.3	7	85.2	7	85.2
8	62.9	8	62.9	8	62.9	8	62.9
9	62.9	9	62.9	9	62.9	9	62.8
10	62.8	10	62.8	10	62.7	10	62.8
11	62.8	11	62.8	11	62.7	11	62.8
12	0.0	12	0.0	12	0.0	12	0.0

k = 0.214 W/m-°C k = 0.214 W/m-°C k = 0.214 W/m-°C k = 0.214 W/m-°C

$\overline{T}$ = 73.9 °C $\overline{T}$ = 74.0 °C $\overline{T}$ = 74.0 °C $\overline{T}$ = 74.0 °C

Sample: Polytetrafluoroethylene Date: 5/27/76

Observers: K. W. Jackson

Sample Thickness 0.00772 m

Metered Area 0.003399 m^2

Current 0.245150 Amps

Voltage 17.205 Volts

Power 4.21781 Watts

Room Temperature 25.2 °C

Water Temperature -13.4 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 4.78986

$\overline{k}$ = 0.213 Watts/Meter−°C

$\overline{T}$ = 61.9 °C

Regulated Temperature Controller Settings: Central/Guard Differential 23.0, Left Cold Plate 145.8, Right Cold Plate 146.8

Time: 4:50		Time: 5:20		Time:		Time:	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	73.1	1	73.1	1	73.2	1	73.1
2	73.1	2	73.2	2	73.2	2	73.2
3	73.2	3	73.1	3	73.2	3	73.2
4	73.2	4	73.1	4	73.2	4	73.2
5	63.0	5	63.0	5	63.1	5	63.0
6	73.1	6	73.1	6	73.2	6	73.2
7	73.2	7	73.0	7	73.1	7	73.2
8	50.7	8	50.7	8	50.8	8	50.8
9	50.7	9	50.7	9	50.7	9	50.8
10	50.6	10	50.7	10	50.7	10	50.6
11	50.6	11	50.7	11	50.7	11	50.7
12	-13.6	12	-13.6	12	-13.6	12	-13.6
k = 0.213 W/m-°C		k = 0.213 W/m−°C		k = 0.213 W/m-°C		k = 0.213 W/m-°C	
$\overline{T}$ = 61.9 °C		$\overline{T}$ = 61.9 °C		$\overline{T}$ = 61.9 °C		$\overline{T}$ = 61.9 °C	

Sample: Polytetrafluoroethylene Date: 5/31/76

Observers: K. W. Jackson

Sample Thickness 0.00772 m

Metered Area 0.003399 m^2

Current 0.185350 Amps

Voltage 12.809 Volts

Power 2.37415 Watts

Room Temperature 25.0 °C

Water Temperature -9.9 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$$\frac{qL}{A} = 2.69615$$

$\overline{k}$ = 0.207 Watts/Meter—°C

$\overline{T}$ = 34.1 °C

Regulated Temperature Controller Settings: Central/Guard Differential 23.0, Left Cold Plate 86.0, Right Cold Plate 87.0

Time: 1:20		Time: 1:45		Time: 2:15		Time: 3:00	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	41.5	1	41.5	1	41.5	1	41.5
2	Open Thermocouple	2	Open Thermocouple	2	Open Thermocouple	2	Open Thermocouple
3	41.6	3	41.6	3	41.6	3	41.6
4	41.7	4	41.6	4	41.6	4	41.6
5	37.1	5	37.0	5	37.1	5	37.1
6	41.5	6	41.5	6	41.5	6	41.5
7	41.6	7	41.6	7	41.6	7	41.6
8	28.6	8	28.6	8	28.6	8	28.6
9	28.6	9	28.6	9	28.5	9	28.5
10	28.5	10	28.5	10	28.5	10	28.5
11	28.5	11	28.5	11	28.5	11	28.5
12	-9.9	12	-9.9	12	-9.9	12	-9.9

k = 0.207 W/m-°C k = 0.207 W/m—°C k = 0.207 W/m-°C k = 0.207 W/m-°C

$\overline{T}$ = 34.1 °C $\overline{T}$ = 34.1 °C $\overline{T}$ = 34.1 °C $\overline{T}$ = 34.1 °C

Sample: Polytetrafluoroethylene Date: 6/1/76

Observers: R. Hartlein

Sample Thickness 0.00772 m

Metered Area 0.003399 m^2

Current 0.184305 Amps

Voltage 12.810 Volts

Power 2.36095 Watts

Room Temperature 24.8 °C

Water Temperature 12.6 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 2.68116

$\overline{k}$ = 0.211 Watts/Meter−°C

$\overline{T}$ = 46.6 °C

Regulated Temperature Controller Settings: Central/Guard Differential 23.0, Left Cold Plate 79.5, Right Cold Plate 81.0

Time: 9:00 T/C	Temp.°C	Time: 9:30 T/C	Temp.°C	Time: 10:15 T/C	Temp.°C	Time: 11:00 T/C	Temp.°C
1	52.7	1	52.8	1	52.8	1	52.8
2	Open Thermocouple	2	Open Thermocouple	2	Open Thermocouple	2	Open Thermocouple
3	53.0	3	53.0	3	53.0	3	53.0
4	53.0	4	53.0	4	53.0	4	53.0
5	48.6	5	48.7	5	48.7	5	48.7
6	52.8	6	52.9	6	53.0	6	53.0
7	52.8	7	53.0	7	53.0	7	53.0
8	40.3	8	40.3	8	40.4	8	40.4
9	40.3	9	40.4	9	40.4	9	40.4
10	40.0	10	40.1	10	40.1	10	40.1
11	40.0	11	40.1	11	40.1	11	40.1
12	12.6	12	12.6	12	12.6	12	12.8
k = 0.211 W/m−°C		k = 0.211 W/m−°C		k = 0.211 W/m−°C		k = 0.211 W/m−°C	
$\overline{T}$ = 46.5 °C		$\overline{T}$ = 46.6 °C		$\overline{T}$ = 46.6 °C		$\overline{T}$ = 46.6 °C	

Sample: Ultrahigh Molecular Weight Polyethylene Date: 6/18/76

Observers: K. W. Jackson

Sample Thickness 0.00815 m

Metered Area 0.003399 m^2

Current 0.199860 Amps

Voltage 12.890 Volts

Power 2.57620 Watts

Room Temperature 25.0 °C

Water Temperature -9.6 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 3.0885

$\overline{k}$ = 0.376 Watts/Meter−°C

$\overline{T}$ = 30.3 °C

Regulated Temperature Controller Settings: Central/Guard Differential 26.8, Left Cold Plate Off, Right Cold Plate 83.0

Time: 5:40 T/C	Temp.°C	Time: 6:15 T/C	Temp.°C	Time: 7:20 T/C	Temp.°C	Time: 8:15 T/C	Temp.°C
1	34.3	1	34.4	1	34.4	1	34.3
2	34.3	2	34.3	2	34.4	2	34.3
3	34.4	3	34.4	3	34.5	3	34.4
4	34.4	4	34.4	4	34.5	4	34.4
5	32.1	5	32.1	5	32.2	5	32.2
6	34.4	6	34.4	6	34.5	6	34.4
7	34.4	7	34.4	7	34.5	7	34.4
8	26.1	8	26.2	8	26.2	8	26.2
9	26.1	9	26.2	9	26.2	9	26.2
10	26.1	10	26.2	10	26.1	10	26.1
11	26.1	11	26.2	11	26.1	11	26.1
12	-9.5	12	-9.5	12	-9.5	12	-9.5

k = 0.375 W/m−°C k = 0.377 W/m−°C k = 0.375 W/m−°C k = 0.375 W/m−°C

$\overline{T}$ = 30.2 °C $\overline{T}$ = 30.3 °C $\overline{T}$ = 30.3 °C $\overline{T}$ = 30.3 °C

Sample: Ultrahigh Molecular Weight Polyethylene

Date: 6/20/76

Observers: K. W. Jackson

Sample Thickness 0.00815 m

Metered Area 0.003399 m^2

Current 0.197220 Amps

Voltage 12.844 Volts

Power 2.53310 Watts

Room Temperature 25.0 °C

Water Temperature 10.8 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$$\frac{qL}{A} = 3.03816$$

$\bar{k}$ = 0.367 Watts/Meter−°C

$\bar{\bar{T}}$ = 43.9 °C

Regulated Temperature Controller Settings: Central/Guard Differential 26.8, Left Cold Plate Off, Right Cold Plate Off

Time: 10:20		Time: 10:53		Time: 11:25		Time: 12:15	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	48.0	1	47.9	1	48.0	1	48.0
2	48.1	2	48.0	2	48.0	2	48.1
3	48.2	3	48.2	3	48.1	3	48.2
4	48.1	4	48.1	4	48.1	4	48.1
5	44.3	5	44.3	5	44.2	5	44.3
6	48.1	6	48.1	6	48.1	6	48.1
7	48.0	7	48.0	7	48.0	7	48.1
8	39.8	8	39.8	8	39.8	8	39.8
9	39.8	9	39.8	9	39.8	9	39.8
10	39.8	10	39.8	10	39.8	10	39.8
11	39.8	11	39.7	11	39.8	11	39.8
12	10.8	12	10.8	12	10.8	12	10.8
k = 0.366 W/m−°C		k = 0.367 W/m−°C		k = 0.368 W/m−°C		k = 0.368 W/m−°C	
$\bar{T}$ = 43.9 °C		$\bar{T}$ = 43.9 °C		$\bar{T}$ = 43.9 °C		$\bar{T}$ = 43.9 °C	

Sample: Ultrahigh Molecular Weight Polyethylene   Date: 6/22/76

Observers: K. W. Jackson

Sample Thickness 0.00815 m

Metered Area 0.003399 m^2

Current 0.265297 Amps

Voltage 16.997 Volts

Power 4.50925 Watts

Room Temperature 24.5 °C

Water Temperature 9.3 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 5.4061

$\overline{k}$ = .384 Watts/Meter − °C

$\overline{T}$ = 21.3 °C

Regulated Temperature Controller Settings: Central/Guard Differential 29.0, Left Cold Plate Off, Right Cold Plate 64.4

Time: 7:00		Time: 7:30		Time: 8:00		Time: 8:30	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	29.2	1	29.2	1	29.3	1	29.3
2	29.3	2	29.2	2	29.3	2	29.3
3	Open Thermocouple	3	Open Thermocouple	3	Open Thermocouple	3	Open Thermocouple
4	29.4	4	29.5	4	29.5	4	29.5
5	22.7 room	5	22.7	5	22.7	5	22.8
6	29.3	6	29.4	6	29.5	6	29.5
7	29.35	7	29.4	7	29.5	7	29.4
8	15.2	8	15.3	8	15.2	8	15.3
9	15.2	9	15.3	9	15.2	9	15.2
10	15.2	10	15.3	10	15.4	10	15.3
11	15.2	11	15.3	11	15.3	11	15.3
12	9.35	12	9.4	12	9.4	12	9.4

k = 0.384 W/m−°C k = 0.384 W/m−°C k = .383 W/m−°C k = 0.383 W/m−°C

$\overline{T}$ = 21.2 °C $\overline{T}$ = 21.3 °C $\overline{T}$ = 21.3 °C $\overline{T}$ = 21.3 °C

Sample: Ultrahigh Molecular Weight Polyethylene Date: 6/22/76

Observers: K. W. Jackson

Sample Thickness 0.00815 m

Metered Area 0.003399 m^2

Current 0.261528 Amps

Voltage 16.998 Volts

Power 4.44545 Watts

Room Temperature 24.6 °C

Water Temperature 49.4 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$$\frac{qL}{A} = 5.33180$$

$\overline{k} = 0.349$ Watts / Meter − °C

$\overline{T} = 58.2$ °C

Regulated Temperature Controller Settings: Central/Guard Differential 20.0, Left Cold Plate Off, Right Cold Plate Off

Time: 12:30		Time: 1:00		Time: 1:30		Time: 2:00	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	65.8	1	65.7	1	65.7	1	65.7
2	65.8	2	65.8	2	65.8	2	65.8
3	66.0	3	66.0	3	66.0	3	66.0
4	66.0	4	66.0	4	66.0	4	66.0
5	58.9	5	58.9	5	58.8	5	58.9
6	65.9	6	65.9	6	65.9	6	65.9
7	66.0	7	66.0	7	66.0	7	66.0
8	50.6	8	50.6	8	50.6	8	50.6
9	50.6	9	50.6	9	50.6	9	50.6
10	50.7	10	50.6	10	50.6	10	50.7
11	50.7	11	50.6	11	50.6	11	50.6
12	49.4	12	49.4	12	49.4	12	49.4
k = 0.349 W/m−°C		k = 0.350 W/m−°C		k = 0.349 W/m−°C		k = 0.349 W/m−°C	
$\overline{T}$ = 58.3 °C		$\overline{T}$ = 58.2 °C		$\overline{T}$ = 58.2 °C		$\overline{T}$ = 58.2 °C	

Sample: Ultrahigh Molecular Weight Polyethylene

Date: 6/24/76

Observers: K. W. Jackson

Sample Thickness 0.00815 m

Metered Area 0.003399 m^2

Current 0.259408 Amps

Voltage 16.999 Volts

Power 4.40968 Watts

Room Temperature 26.2 °C

Water Temperature 69.7 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 5.28890

$\overline{k}$ = 0.331 Watts/Meter − °C

$\overline{T}$ = 77.3 °C

Regulated Temperature Controller Settings: Central/Guard Differential 29.0, Left Cold Plate Off, Right Cold Plate Off

Time: 11:15		Time: 11:45		Time: 12:25		Time: 1:15	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	85.1	1	85.1	1	85.1	1	85.1
2	85.2	2	85.2	2	85.1	2	85.2
3	85.4	3	85.4	3	85.4	3	85.3
4	85.5	4	85.4	4	85.4	4	85.3
5	26.2	5	25.8	5	25.6	5	85.5
6	85.2	6	85.3	6	85.2	6	26.2
7	85.3	7	85.4	7	85.3	7	85.3
8	69.3	8	69.3	8	69.3	8	69.3
9	69.3	9	69.3	9	69.3	9	69.3
10	69.3	10	69.3	10	69.3	10	69.3
11	69.3	11	69.3	11	69.3	11	69.3
12	69.7	12	69.8	12	69.7	12	69.7
k = 0.331 W/m-°C		k = 0.331 W/m-°C		k = 0.332 W/m-°C		k = 0.331 W/m-°C	
$\overline{T}$ = 77.3 °C		$\overline{T}$ = 77.3 °C		$\overline{T}$ = 77.3 °C		$\overline{T}$ = 77.3 °C	

Sample: Polytetrafluoroethylene Date: 7/4/76

Observers: K. W. Jackson

Sample Thickness 0.00772 m

Metered Area 0.003399 m^2

Current 0.262987 Amps

Voltage 16.984 Volts

Power 4.46657 Watts

Room Temperature 25.0 °C

Water Temperature 5.5 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$$\frac{qL}{A} = 5.07235$$

$\overline{k}$ = 0.207 Watts/Meter − °C

$\overline{T}$ = 27.1 °C

Regulated Temperature Controller Settings: Central/Guard Differential 29.0, Left Cold Plate 63.0, Right Cold Plate 56.8

Time: 7:35		Time: 8:05		Time: 8:35		Time: 9:05	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	39.3	1	39.4	1	39.3	1	39.3
2	39.3	2	39.4	2	39.4	2	39.4
3	39.4	3	39.4	3	39.4	3	39.4
4	39.4	4	39.4	4	39.4	4	39.3
5	30.4	5	30.5	5	39.4	5	39.4
6	39.3	6	39.4	6	39.4	6	39.4
7	39.4	7	39.5	7	39.5	7	39.4
8	14.9	8	14.9	8	14.9	8	14.9
9	14.9	9	14.9	9	14.9	9	14.9
10	14.8	10	14.8	10	14.8	10	14.8
11	14.8	11	14.7	11	14.8	11	14.9
12	5.5	12	5.5	12	5.5	12	5.5

k = 0.207 W/m−°C k = 0.206 W/m−°C k = 0.207 W/m−°C k = 0.207 W/m−°C

$\overline{T}$ = 27.1 °C $\overline{T}$ = 27.1 °C $\overline{T}$ = 27.1 °C $\overline{T}$ = 27.1 °C

Sample: Polytetrafluoroethylene Date: 7/5/76

Observers: K. W. Jackson

Sample Thickness 0.00772 m

Metered Area 0.003399 m^2

Current 0.261148 Amps

Voltage 16.984 Volts

Power 4.43533 Watts

Room Temperature 25.0 °C

Water Temperature 24.6 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 5.03688

$\overline{k}$ = 0.209 Watts /Meter—°C

$\overline{T}$ = 43.1 °C

Regulated Temperature Controller Settings: Central/Guard Differential 29.0, Left Cold Plate 90.8, Right Cold Plate 89.8

Time: 3:00		Time: 3:30		Time: 4:00		Time: 4:30	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	55.0	1	55.1	1	55.0	1	55.1
2	55.1	2	55.2	2	55.0	2	55.2
3	55.4	3	55.5	3	55.4	3	55.4
4	55.4	4	55.4	4	55.5	4	55.5
5	46.5	5	46.5	5	46.5	5	46.5
6	55.2	6	55.2	6	55.2	6	55.2
7	55.3	7	55.3	7	55.3	7	55.2
8	31.0	8	31.0	8	31.0	8	31.0
9	31.0	9	31.0	9	31.0	9	31.0
10	31.0	10	31.0	10	31.0	10	31.0
11	31.0	11	31.0	11	31.0	11	31.0
12	24.7	12	24.7	12	24.7	12	24.7

k = .209 W/m–°C k = .209 W/m–°C k = .209 W/m–°C k = .209 W/m–°C

$\overline{T}$ = 43.1 °C $\overline{T}$ = 43.1 °C $\overline{T}$ = 43.1 °C $\overline{T}$ = 43.1 °C

Sample: T. F. E. Date: 7/6/76

Observers: K. W. Jackson

Sample Thickness 0.00772 m

Metered Area 0.003399 m^2

Current 0.259448 Amps

Voltage 16.983 Volts

Power 4.40621 Watts

Room Temperature 24.3 °C

Water Temperature 44.8 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 5.00381

$\overline{k}$ = 0.212 Watts/Meter-°C

$\overline{T}$ = 63.7 °C

Regulated Temperature Controller Settings: Central/Guard Differential 29.0, Left Cold Plate 126.8, Right Cold Plate 127.0

Time: 7:30		Time: 8:00		Time: 9:00		Time: 9:50	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	75.4	1	75.5	1	75.5	1	75.5
2	75.5	2	75.5	2	75.5	2	75.6
3	75.7	3	75.8	3	75.7	3	75.7
4	75.6	4	75.6	4	75.7	4	75.7
5	67.9	5	68.1	5	68.1	5	68.1
6	75.5	6	75.6	6	75.6	6	75.7
7	75.6	7	75.7	7	75.7	7	75.8
8	51.9	8	51.8	8	51.9	8	51.9
9	51.9	9	51.8	9	51.9	9	51.9
10	52.0	10	51.9	10	52.0	10	52.0
11	51.9	11	51.9	11	52.0	11	52.0
12	44.8	12	44.8	12	44.7	12	44.7
k = 0.212 W/m-°C		k = 0.212 W/m-°C		k = 0.212 W/m-°C		k = 0.211 W/m-°C	
$\overline{T}$ = 63.7 °C		$\overline{T}$ = 63.7 °C		$\overline{T}$ = 63.8 °C		$\overline{T}$ = 63.7 °C	

Sample: Polytetrafluoroethylene Date: 7/6/76

Observers: K. W. Jackson

Sample Thickness 0.00772 m

Metered Area 0.003399 m^2

Current 0.257048 Amps

Voltage 16.984 Volts

Power 4.36571 Watts

Room Temperature 25.2 °C

Water Temperature 67.6 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 4.99122

$\overline{k}$ = 0.215 Watts/Meter − °C

$\overline{T}$ = 86.7 °C

Regulated Temperature Controller Settings: Central/Guard Differential 23.0, Left Cold Plate 163.8, Right Cold Plate 165.0

Time: 12:40 T/C	Temp.°C	Time: 1:22 T/C	Temp.°C	Time: 1:55 T/C	Temp.°C	Time: 2:35 T/C	Temp.°C
1	96.1	1	96.1	1	96.0	1	96.1
2	96.2	2	96.1	2	96.1	2	96.2
3	96.5	3	96.5	3	96.4	3	96.4
4	96.3	4	96.3	4	96.3	4	96.4
5	88.7	5	88.8	5	88.7	5	88.7
6	96.2	6	96.1	6	96.1	6	96.2
7	96.2	7	96.2	7	96.1	7	96.2
8	73.1	8	73.1	8	73.0	8	73.0
9	73.1	9	73.1	9	73.0	9	73.0
10	73.2	10	73.1	10	73.1	10	73.1
11	73.0	11	73.1	11	73.1	11	73.0
12	67.6	12	67.6	12	67.6	12	67.6

k = 0.215 W/m-°C k = 0.215 W/m-°C k = 0.215 W/m-°C k = 0.215 W/m-°C

$\overline{T}$ = 86.6 °C $\overline{T}$ = 86.6 °C $\overline{T}$ = 86.7 °C $\overline{T}$ = 86.7 °C

Sample: 40% Continuous Glass Fiber/ 0.5% Carbon Black/ 59.5% Polypropylene

Date: 7/14/76

Observers: K. W. Jackson

Sample Thickness 0.01006 m

Metered Area 0.003399 m^2

Current 0.24175 Amps

Voltage 16.990 Volts

Power 4.10736 Watts

Room Temperature 26.0 °C

Water Temperature 31.3 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 6.078265

$\overline{k}$ = 0.241 Watts/Meter-°C

$\overline{T}$ = 48.9 °C

Regulated Temperature Controller Settings: Central/Guard Differential 23.0, Left Cold Plate 107.2, Right Cold Plate 107.0

Time: 1:10		Time: 1:40		Time: 2:10		Time: 2:50	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	61.4	1	61.4	1	61.4	1	61.4
2	61.6	2	61.6	2	61.6	2	61.6
3	61.5	3	61.5	3	61.5	3	61.5
4	61.6	4	61.6	4	61.6	4	61.6
5	50.2	5	50.1	5	50.1	5	50.2
6	61.5	6	61.5	6	61.5	6	61.5
7	61.4	7	61.4	7	61.4	7	61.4 ✓
8	36.3	8	36.3	8	36.3	8	36.2
9	36.2	9	36.2	9	36.2	9	36.2
10	36.4	10	36.3	10	36.2	10	36.3
11	36.3	11	36.3	11	36.2	11	36.2
12	31.2	12	31.3	12	31.2	12	31.2
k = 0.241 W/m-°C		k = 0.241 W/m-°C		k = 0.240 W/m-°C		k = 0.240 W/m-°C	
$\overline{T}$ = 48.9 °C		$\overline{T}$ = 48.9 °C		$\overline{T}$ = 48.9 °C		$\overline{T}$ = 48.9 °C	

Sample: 40% Continuos Glass Fiber/ 0.5% Carbon Black/ 59.5% Polypropylene

Date: 7/14/76

Observers: K. W. Jackson

Sample Thickness 0.01006 m

Metered Area 0.003399 m^2

Current 0.23965 Amps

Voltage 16.991 Volts

Power 4.07192 Watts

Room Temperature 26.2 °C

Water Temperature 50.1 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$$\frac{qL}{A} = 6.02583$$

$\bar{k}$ = 0.237 Watts/Meter − °C

$\bar{T}$ = 70.7 °C

Regulated Temperature Controller Settings: Central/Guard Differential 25.0, Left Cold Plate 136.0, Right Cold Plate 136.0

T/C	Time: 4:10 Temp. °C	T/C	Time: 4:50 Temp. °C	T/C	Time: 5:20 Temp. °C	T/C	Time: 5:50 Temp. °C
1	82.6	1	82.6	1	82.7	1	82.7
2	83.1	2	83.0	2	83.2	2	83.2
3	82.7	3	82.7	3	82.8	3	82.8
4	82.8	4	82.9	4	82.9	4	82.9
5	71.3	5	71.3	5	71.3	5	71.4
6	82.8	6	82.7	6	82.9	6	82.9
7	82.8	7	82.8	7	82.8	7	83.0
8	57.4	8	57.4	8	57.4	8	57.4
9	57.3	9	57.3	9	57.3	9	57.4
10	57.4	10	57.4	10	57.4	10	57.5
11	57.4	11	57.4	11	57.4	11	57.5
12	49.7	12	49.7	12	50.1	12	50.1

k = 0.239 W/m-°C k = 0.237 W/m-°C k = 0.236 W/m-°C k = 0.237 W/m-°C

$\bar{T}$ = 70.05 °C $\bar{T}$ = 70.1 °C $\bar{T}$ = 70.1 °C $\bar{T}$ = 70.1 °C

Sample: 40% Continuous Glass Fiber/ 0.5% Carbon Black/ 59.5% Polypropylene

Date: 7/15/76

Observers: K. W. Jackson

Sample Thickness 0.01006 m

Metered Area 0.003399 m^2

Current 0.237652 Amps

Voltage 16.992 Volts

Power 4.038190 Watts

Room Temperature 24.6 °C

Water Temperature 69.4 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 5.97590

$\overline{k}$ = 0.231 Watts/Meter − °C

$\overline{T}$ = 90.5 °C

Regulated Temperature Controller Settings: Central/Guard Differential 25.0, Left Cold Plate 172.0, Right Cold Plate 172.2

Time: 7:30		Time: 9:00		Time: 10:00		Time: 10:30	
T/C	Temp. °C	T/C	Temp. °C	T/C	Temp. °C	T/C	Temp. °C
1	103.2	1	103.2	1	103.2	1	103.2
2	103.8	2	103.8	2	103.8	2	103.8
3	103.8	3	103.4	3	103.4	3	103.4
4	103.5	4	103.5	4	103.4	4	103.4
5	91.8	5	91.8	5	91.8	5	91.7
6	103.4	6	103.4	6	103.4	6	103.4
7	103.4	7	103.5	7	103.4	7	103.4
8	77.6	8	77.5	8	77.6	8	77.6
9	77.6	9	77.6	9	77.6	9	77.6
10	77.5	10	77.6	10	77.6	10	77.6
11	77.5	11	77.7	11	77.6	11	77.6
12	69.4	12	69.4	12	69.4	12	69.4
k = 0.231 W/m-°C		k = 0.231 W/m-°C		k = 0.231 W/m-°C		k = 0.231 W/m-°C	
$\overline{T}$ = 90.5 °C		$\overline{T}$ = 90.5 °C		$\overline{T}$ = 90.5 °C		$\overline{T}$ = 90.5 °C	

Sample: 40% Continuous Glass Fiber/ 0.5% Carbon Black/ 59.5% Polypropylene Date: 7/16/76

Observers: K. W. Jackson

Sample Thickness 0.01006 m

Metered Area 0.003399 m^2

Current 0.243451 Amps

Voltage 16.991 Volts

Power 4.13648 Watts

Room Temperature 24.6 °C

Water Temperature 8.8 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 6.12387

$\overline{k}$ = 0.245 Watts/Meter—°C

$\overline{T}$ = 27.4 °C

Regulated Temperature Controller Settings: Central/Guard Differential 25.0, Left Cold Plate 162.8, Right Cold Plate 163.2

Time: 11:45		Time: 1:20		Time: 1:50		Time: 2:20	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	39.8	1	39.7	1	39.7	1	39.8
2	40.1	2	40.1	2	40.1	2	40.1
3	39.9	3	39.9	3	39.9	3	39.9
4	40.1	4	40.1	4	40.1	4	40.1
5	28.6	5	28.6	5	28.6	5	28.6
6	39.9	6	38.8	6	39.9	6	38.8
7	39.8	7	39.8	7	39.8	7	39.8
8	14.9	8	15.0	8	15.0	8	14.9
9	14.9	9	15.0	9	15.0	9	14.9
10	14.8	10	14.9	10	14.9	10	14.9
11	14.8	11	14.9	11	14.9	11	14.9
12	8.7	12	8.8	12	8.8	12	8.7

k = 0.245 W/m-°C	k = 0.245 W/m—°C	k = 0.245 W/m-°C	k = 0.245 W/m-°C
$\overline{T}$ = 27.4 °C	$\overline{T}$ = 27.4 °C	$\overline{T}$ = 27.4 °C	$\overline{T}$ = 27.4 °C

Sample: 40% Continuous Glass Fiber Reinforced Polypropylene

Date: 7/21/76

Observers: K. W. Jackson

Sample Thickness 0.01006 m

Metered Area 0.003399 m^2

Current 0.243351 Amps

Voltage 16.989 Volts

Power 4.134296 Watts

Room Temperature 25.0 °C

Water Temperature 8.8 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$$\frac{qL}{A} = 6.11813$$

$\overline{k} =$ 0.239 Watts/Meter−°C

$\overline{T} =$ 28.7 °C

Regulated Temperature Controller Settings: Central/Guard Differential 27.0, Left Cold Plate 65.0, Right Cold Plate 65.0

Time: 8:00		Time: 10:00		Time: 10:30		Time: 11:00	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	41.3	1	41.3	1	41.3	1	41.3
2	41.3	2	41.4	2	41.3	2	41.3
3	31.7	3	41.7	3	41.7	3	41.7
4	41.5	4	41.6	4	41.5	4	41.6
5	29.2	5	29.2	5	29.0	5	29.2
6	41.4	6	41.5	6	41.4	6	41.5
7	41.5	7	41.5	7	41.5	7	41.5
8	16.1	8	16.0	8	16.0	8	16.0
9	16.1	9	16.0	9	16.0	9	16.0
10	15.9	10	15.8	10	15.8	10	15.8
11	15.7	11	15.6	11	15.6	11	15.6
12	8.8	12	8.7	12	8.7	12	8.7

k = 0.240 W/m−°C   k = 0.239 W/m−°C   k = 0.239 W/m−°C   k = 0.239 W/m−°C

$\overline{T} =$ 28.7 °C $\overline{T} =$ 28.7 °C $\overline{T} =$ 28.7 °C $\overline{T} =$ 28.7 °C

Sample: 40% Continuous Glass Fiber Reinforced Polypropylene Date: 7/21/76

Observers: K. W. Jackson

Sample Thickness 0.01006 m

Metered Area 0.003399 m^2

Current 0.024125 Amps

Voltage 16.989 Volts

Power 4.098626 Watts

Room Temperature 25.0 °C

Water Temperature 28.5 °C

Regulated Temperature Controller Settings: Central/Guard Differential 26.0, Left Cold Plate 101.0, Right Cold Plate 101.2

$$k = \frac{qL}{A(T_h - T_c)}$$

$$\frac{qL}{A} = 6.06534$$

$\overline{k}$ = 0.237 Watts/Meter — °C

$\overline{T}$ = 49.8 °C

Time: 8:00		Time: 9:00		Time: 10:00		Time: 10:30	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	62.5	1	62.5	1	62.6	1	62.4
2	62.5	2	62.5	2	62.5	2	62.4
3	62.8	3	62.8	3	62.8	3	62.7
4	62.8	4	62.7	4	62.8	4	62.7
5	50.1	5	50.2	5	50.1	5	50.2
6	62.6	6	62.6	6	62.7	6	62.5
7	62.6	7	62.7	7	62.8	7	62.5
8	37.2	8	37.1	8	37.2	8	37.1
9	37.2	9	37.1	9	37.2	9	37.0
10	36.9	10	36.9	10	36.9	10	36.9
11	36.9	11	36.9	11	36.9	11	36.9
12	28.5	12	28.5	12	28.6	12	28.5
k = 0.237 W/m-°C		k = 0.237 W/m-°C		k = 0.237 W/m-°C		k = 0.237 W/m-°C	
$\overline{T}$ = 49.8 °C		$\overline{T}$ = 49.8 °C		$\overline{T}$ = 49.9 °C		$\overline{T}$ = 49.8 °C	

Sample: 40% Continuous Glass Fiber Reinforced Polypropylene Date: 7/22/76

Observers: K. W. Jackson

Sample Thickness 0.01006 m

Metered Area 0.003399 m^2

Current 0.239452 Amps

Voltage 16.990 Volts

Power 4.06914 Watts

Room Temperature 26.0 °C

Water Temperature 51.6 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$$\frac{qL}{A} = 6.02045$$

$\overline{k}$ = 0.232 Watts/Meter — °C

$\overline{T}$ = 71.7 °C

Regulated Temperature Controller Settings: Central/Guard Differential 26.0, Left Cold Plate 138.4, Right Cold Plate 137.9

Time: 1:30		Time: 2:00		Time: 2:30		Time: 3:00	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	84.4	1	84.4	1	84.4	1	84.4
2	84.4	2	84.4	2	84.4	2	84.4
3	84.9	3	84.9	3	84.9	3	84.8
4	84.7	4	84.6	4	84.7	4	84.6
5	72.2	5	72.2	5	72.3	5	72.2
6	84.5	6	84.6	6	84.6	6	84.5
7	84.6	7	84.6	7	84.7	7	84.6
8	58.9	8	58.8	8	58.8	8	58.8
9	59.0	9	58.9	9	58.9	9	58.9
10	58.7	10	58.6	10	58.7	10	58.6
11	58.5	11	58.4	11	58.4	11	58.4
12	53.1	12	53.4	12	53.1	12	53.0
k = 0.233 W/m-°C		k = 0.232 W/m-°C		k = 0.232 W/m-°C		k = 0.232 W/m-°C	
$\overline{T}$ = 71.7 °C		$\overline{T}$ = 71.6 °C		$\overline{T}$ = 71.7 °C		$\overline{T}$ = 71.7 °C	

Sample: 40% Continuous Glass Fiber Reinforced Polypropylene   Date: 7/23/76

Observers: K. W. Jackson

Sample Thickness 0.01006 m

Metered Area 0.003399 m^2

Current 0.237502 Amps

Voltage 16.991 Volts

Power 4.03596 Watts

Room Temperature 26.0 °C

Water Temperature 73.4 °C

$$k = \frac{qL}{A(T_h - T_c)}$$

$\frac{qL}{A}$ = 5.97176

$\overline{k}$ = 0.228 Watts/Meter − °C

$\overline{T}$ = 92.5 °C

Regulated Temperature Controller Settings: Central/Guard Differential 23.0, Left Cold Plate 175.0, Right Cold Plate 175.8

Time: 11:30		Time: 12:00		Time: 12:30		Time: 1:00	
T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C	T/C	Temp.°C
1	105.4	1	105.3	1	105.3	1	105.3
2	105.4	2	105.3	2	105.3	2	105.3
3	106.0	3	106.0	3	105.8	3	105.8
4	105.6	4	105.7	4	105.6	4	105.5
5	93.0	5	93.0	5	93.1	5	93.0
6	105.6	6	105.6	6	105.5	6	105.5
7	105.7	7	105.6	7	105.6	7	105.6
8	79.5	8	79.5	8	79.5	8	79.4
9	79.7	9	79.6	9	79.6	9	79.5
10	79.4	10	79.3	10	79.3	10	79.3
11	79.0	11	79.0	11	79.0	11	78.9
12	73.4	12	73.4	12	73.3	12	73.3
k = 0.228 W/m−°C		k = 0.228 W/m−°C		k = 0.228 W/m−°C		k = 0.228 W/m−°C	
$\overline{T}$ = 92.5 °C		$\overline{T}$ = 92.5 °C		$\overline{T}$ = 92.4 °C		$\overline{T}$ = 92.4 °C	

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